

National Aeronautics and Space Administration



# Bone *Changes* During Spaceflight: How do we assess fracture probability in astronauts?

Navy and WSU Aerospace Medicine

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# At the end of this lecture, you should understand:

- The view of DXA BMD as a surrogate for fracture risk in terrestrial medicine. *Why DXA is not a good research technology to understand fracture risk in astronauts.*
- Flight data describing the unique effects of spaceflight on skeletal sites at risk for age-related osteoporosis on Earth.
- Bold research approaches to assessing the “biomechanical competence of bone” in the context of NASA’s constraints.

Getting on the same page.

# **BONE BIOLOGY**

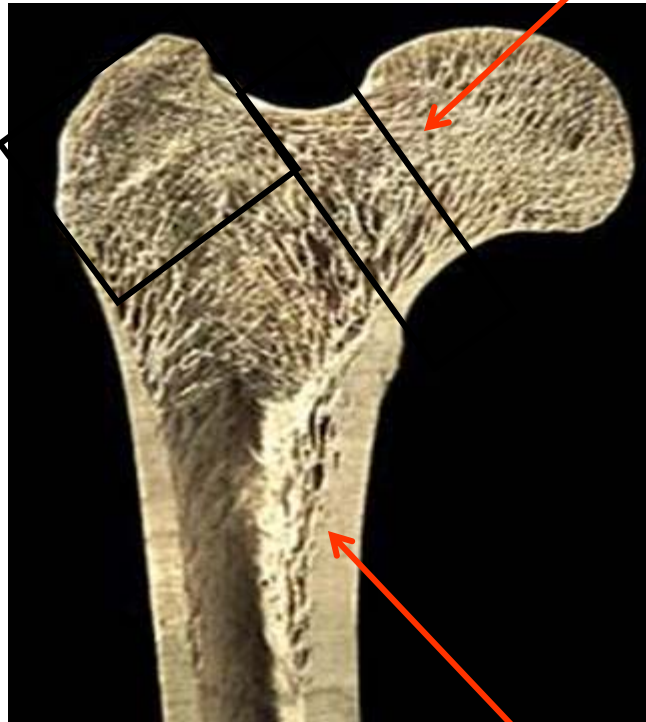
# TWO TYPES OF BONE

Cancellous "Spongy" Bone/Trabecular Bone

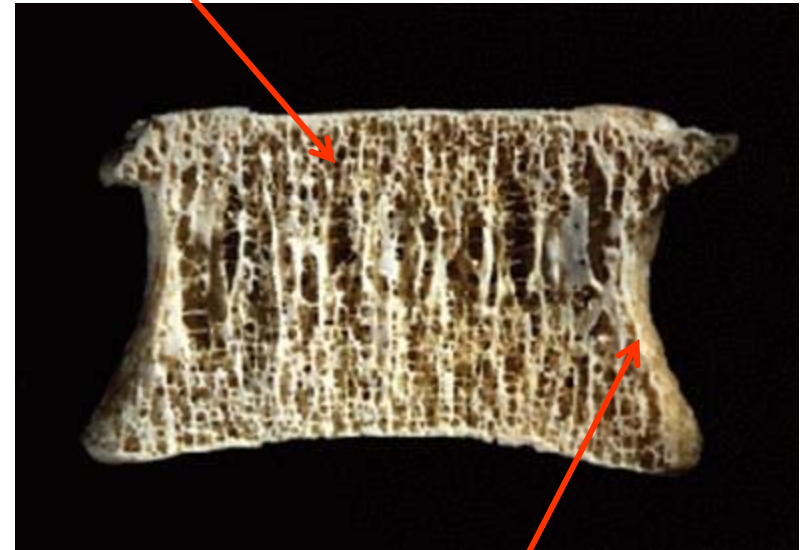
PROXIMAL FEMUR

Trochanter  
50% BMD

Femoral Neck  
25% BMD



VERTEBRAL BODY – 66% BMD



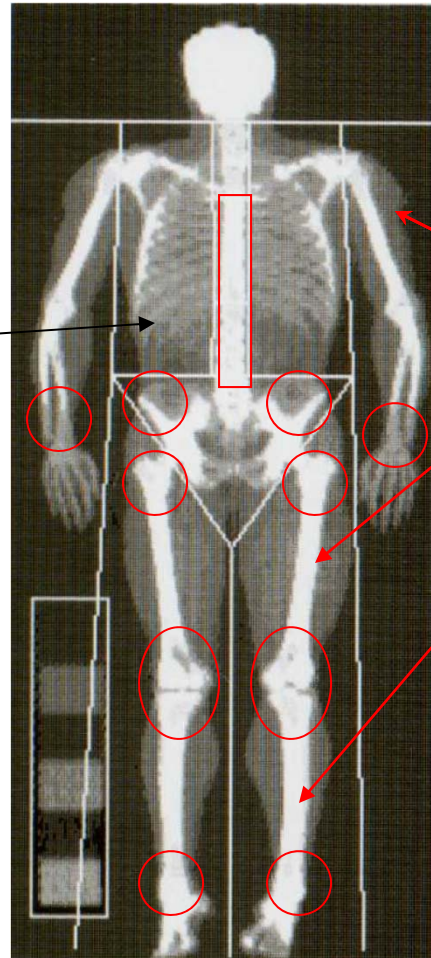
Cortical Bone/ "Compact Bone"

Sources: L. Mosekilde; SL Bonnick; P Crompton

# Distribution of bone types in skeleton and turnover rates on earth

Entire skeleton turns-over  
10%/year: 3% cortex but  
25% of cancellous bone

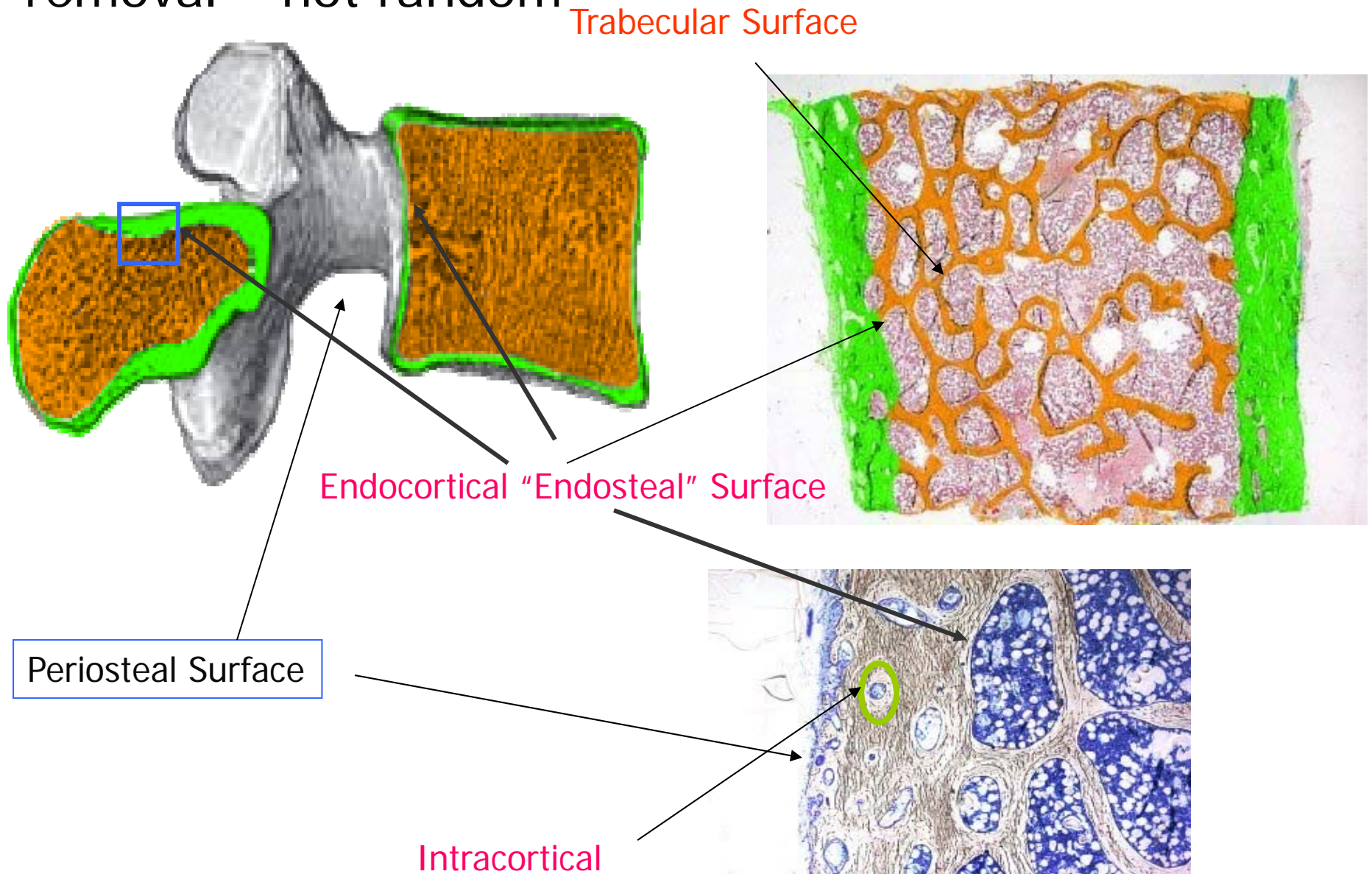
Cancellous Bone 20% of  
total skeleton (vertebrae,  
ribs, ends of long bones)  
**Contains 80% of bone  
surfaces**



Cortical Bone 80% of  
total skeleton  
(long bones)



# BONE SURFACES – Sites of bone formation & removal – not random

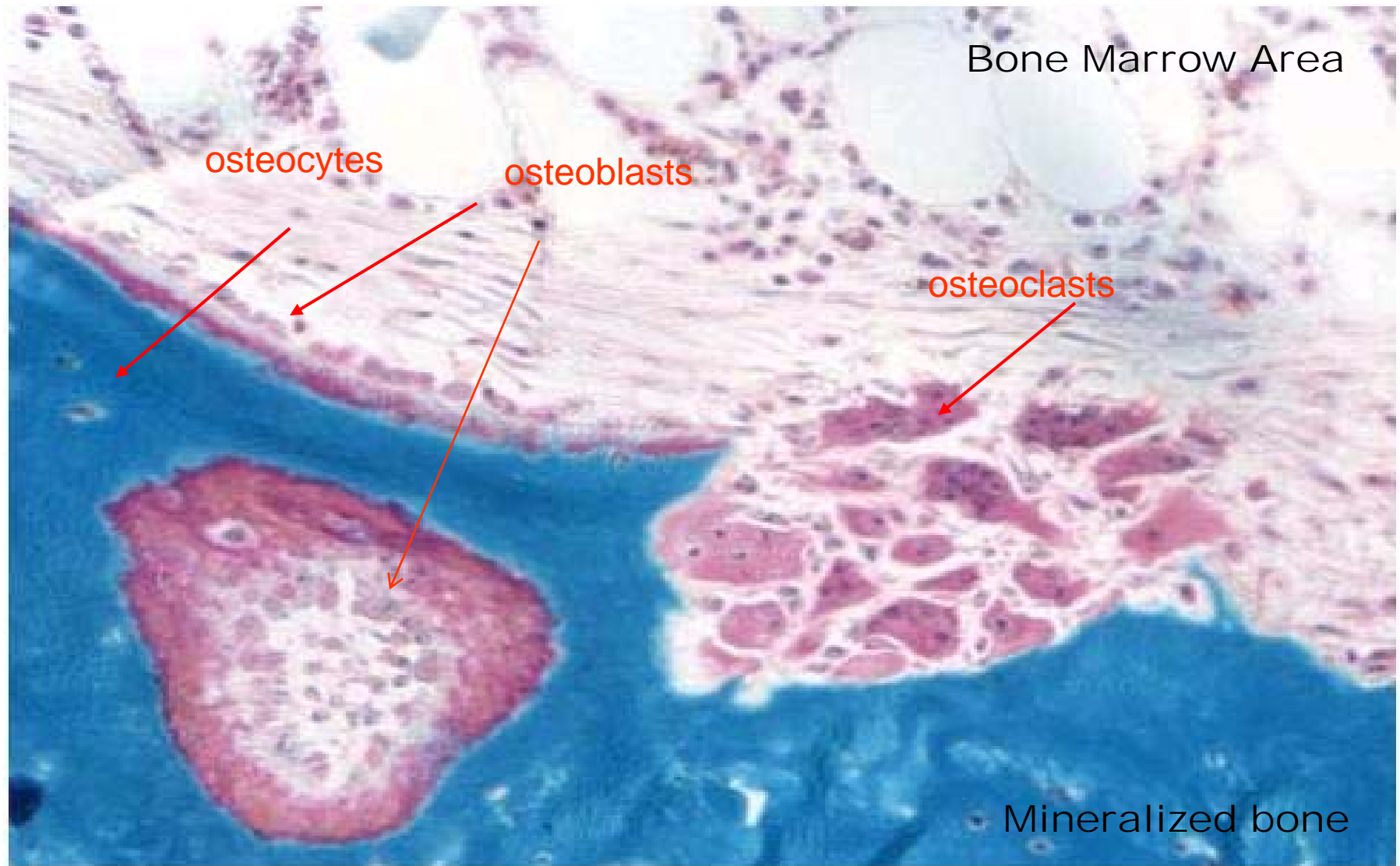


# Remodeling at the level of a single “Bone Remodeling Unit”

HIGHLY-REGULATED ACTIONS OF BONE CELLS on BONE TURNOVER.

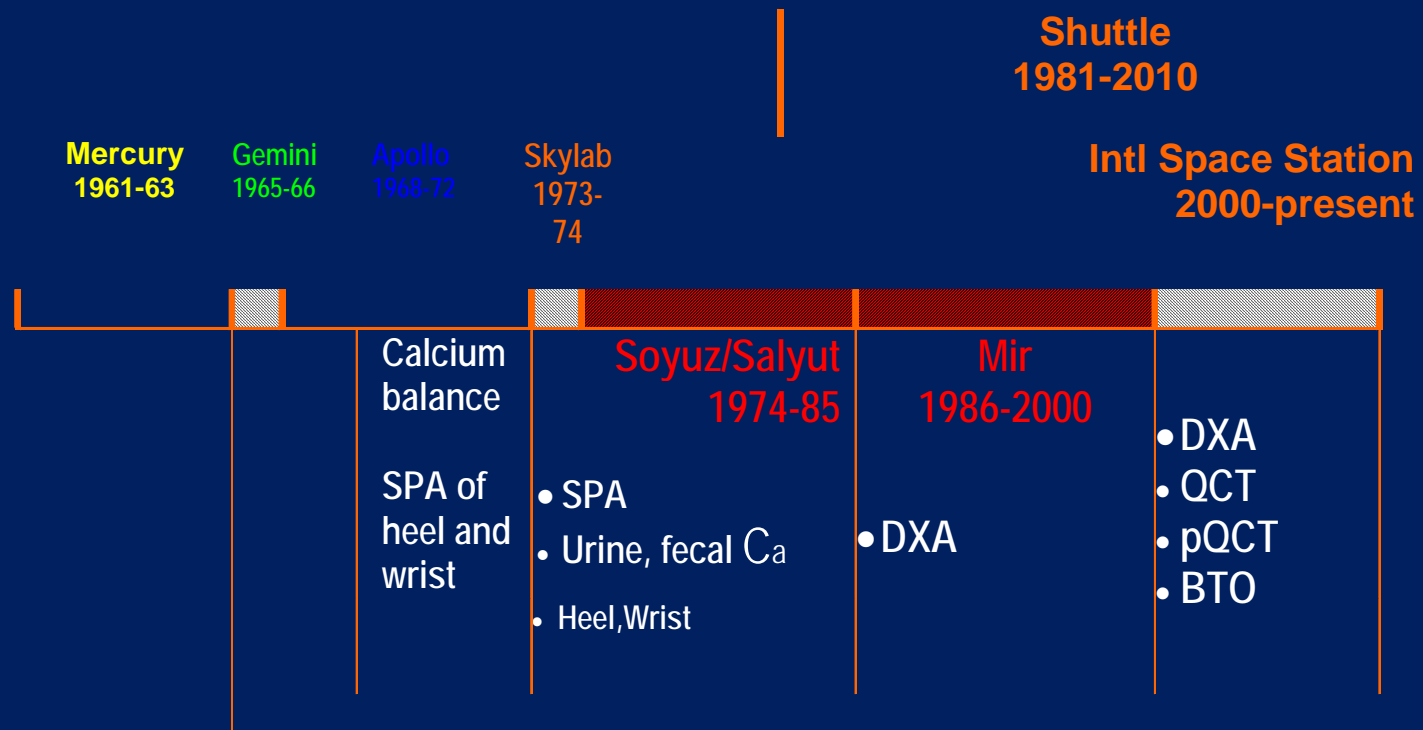


## TYPES OF BONE CELLS: mediators of bone resorption, bone formation, mechanical sensing





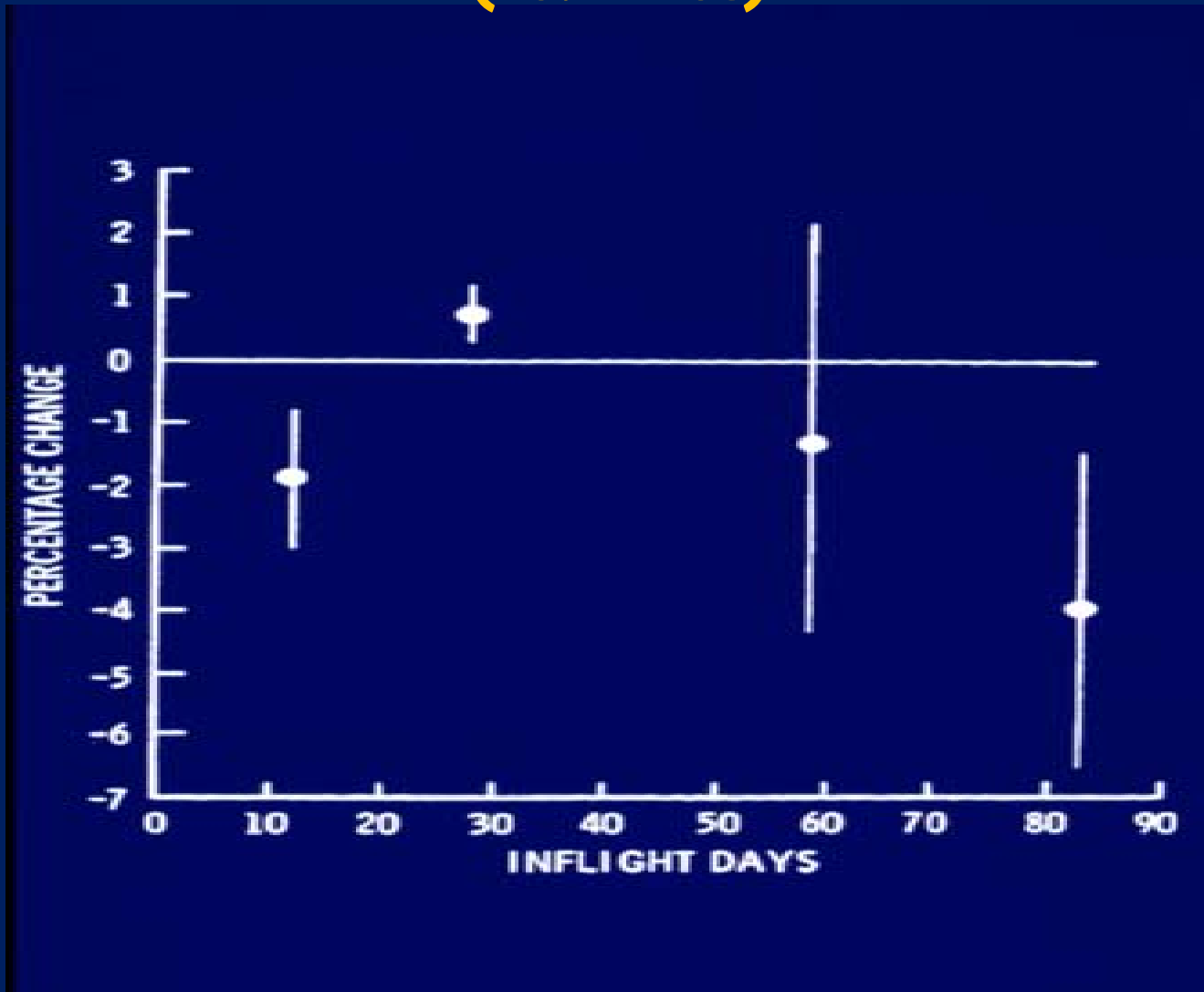
# Characterizing Bone Changes\* in Space



SPA=Single Photon Absorptiometry  
 DXA=Dual-energy X-ray Absorptiometry  
 QCT=Quantitative Computed Tomography  
 pQCT = peripheral QCT  
 BTO=biochemical markers of bone turnover

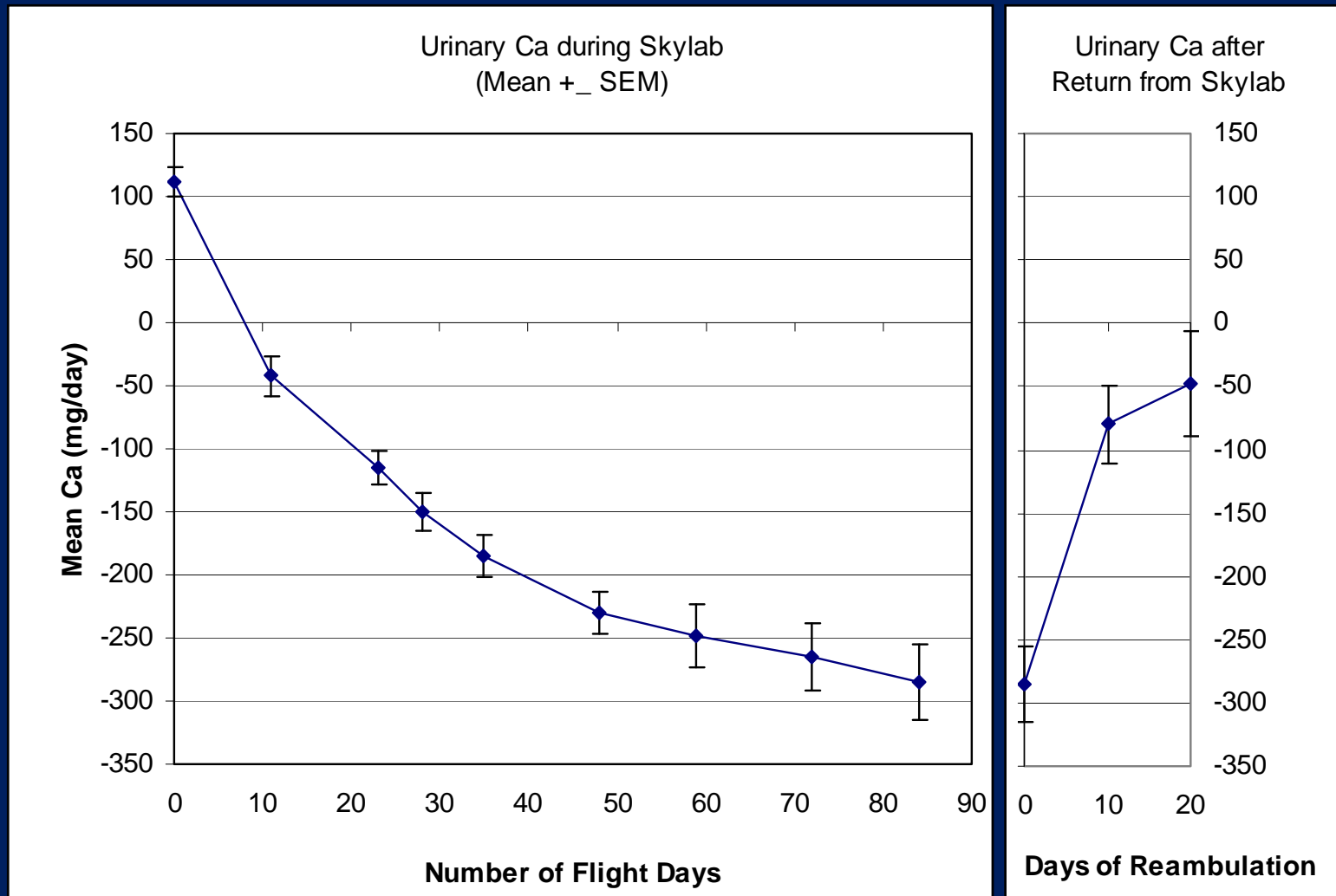
\*Two functions of skeleton

# Skylab-Bone Mineral Density of Calcaneus (vs. wrist)



Rambaut P, Johnston R. Acta Astronaut. 1979;6:1113-22.

# Skylab-Urinary Calcium Excretion



## **Functions of the Skeleton\***

- Internal support for the body
- Attachment for muscles / tendons for motion
- Protects vital organs
- Encloses blood-forming elements in marrow
- Mobilized store for Calcium ( $\text{Ca}^{2+}$ ) homeostasis

\*What potential risks to human health & performance? *During and after a mission.*

## Four identified “Bone” health risks for exploration missions.

1. Early Onset Osteoporosis (fragility fractures)
2. Bone Fracture (trauma fractures)
3. Formation of Renal Stones
4. Intervertebral Disc Injury (*or Damage*)



## Four Identified “Bone” health risks for exploration missions.

1. Early Onset Osteoporosis
2. Bone Fracture
3. Formation of Renal Stones
4. Intervertebral Disc Injury (*or Damage*)

Journal of Bone & Mineral  
June 28(6):1243-1255, 2013

“Bone Summit I – 2010”

REVIEW

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JBMR

**Skeletal Health in Long-Duration Astronauts:  
Nature, Assessment, and Management  
Recommendations from the NASA Bone Summit**

Eric S Orwoll,<sup>1</sup> Robert A Adler,<sup>2</sup> Shreyasee Amin,<sup>3</sup> Neil Binkley,<sup>4</sup> E Michael Lewiecki,<sup>5</sup>  
Steven M Petak,<sup>6</sup> Sue A Shapses,<sup>7</sup> Mehrsheed Sinaki,<sup>8</sup> Nelson B Watts,<sup>9</sup> and Jean D Sibonga<sup>10</sup>

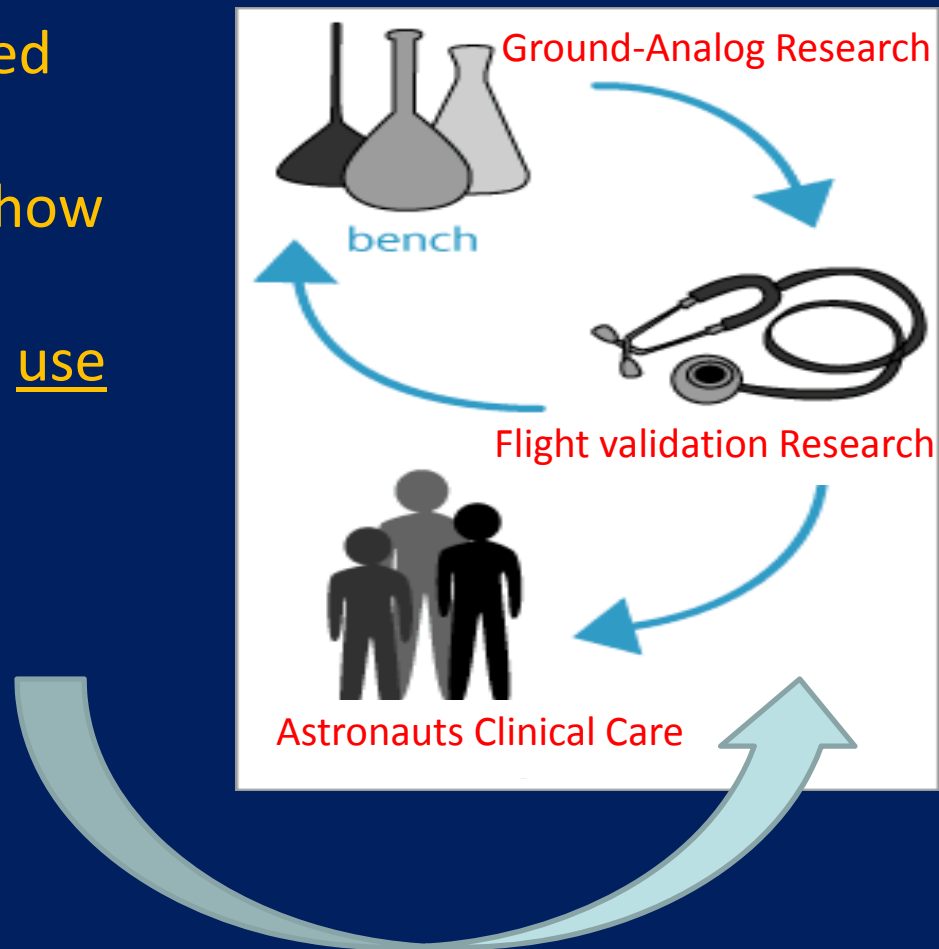
# Combined Medical and Research Tests:

Intervention Requirement?, Clinical Triggers?, Surveillance Recommendations

1. What additional measure(s) do we need to monitor?
2. How frequently? For how long?
3. How should Med Ops use research data in its clinical practice?
4. Need specific clinical practice guidelines.

**BONE SUMMIT  
2010 and 2013**

## Bone Research @ NASA



# Take Home Messages from Bone Summit (2010)

1. Bone is a complicated tissue.
2. NASA has constraints: low subject #'s; slow data acquisition.
3. Astronauts are understudied group.
4. Spaceflight effects on bone are unique.
5. Clinically-accepted tests have limitations.
6. NASA's medical standards for bone health (based upon terrestrial guidelines) are not applicable to long-duration astronauts.
7. *Recommended exploring the transition of research approaches to clinical arena.*

# Risk: Different types of fractures



“Osteoporotic/Fragility Fractures” –  
low to atraumatic Fractures  
due to Osteoporosis  
(Causality - SKELETAL CONDITION)

You don't have to be **OLD**.

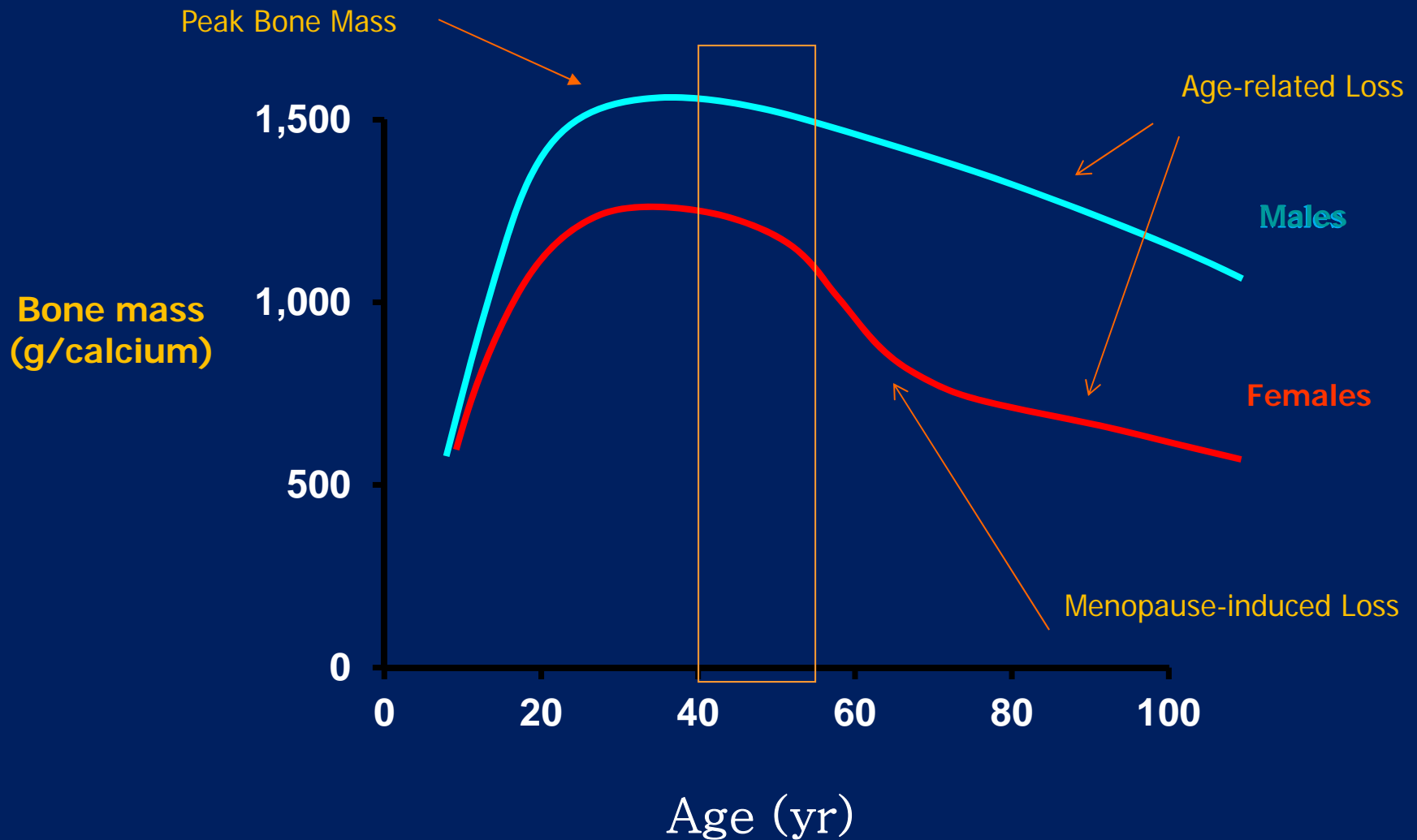


Load > Bone Strength = FRACTURE  
(Causality – BIOMECHANICS)

**You don't have to have OSTEOPOROSIS.**

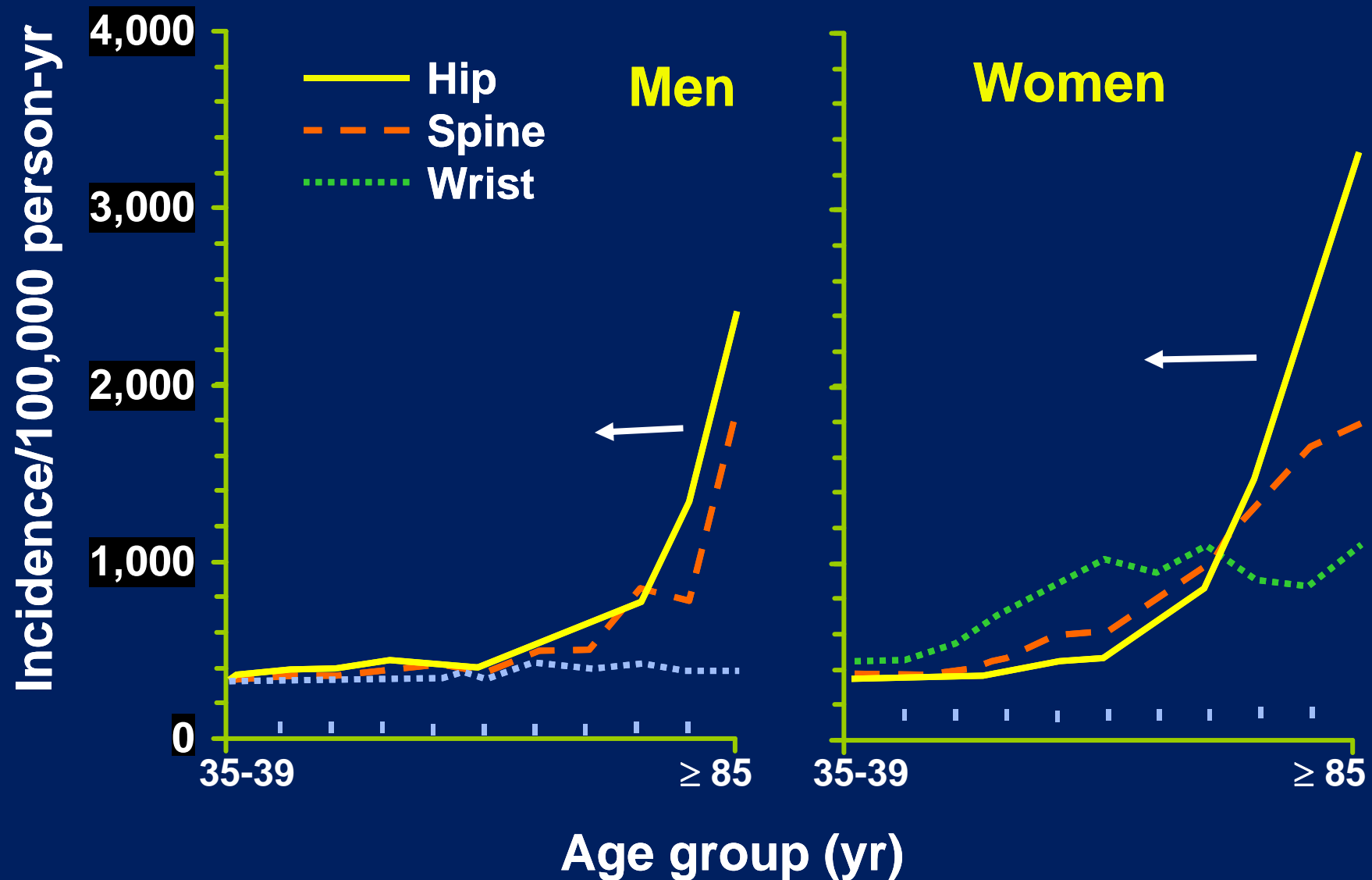


# Does spaceflight result in irreversible changes to bone that combine with age-related losses?

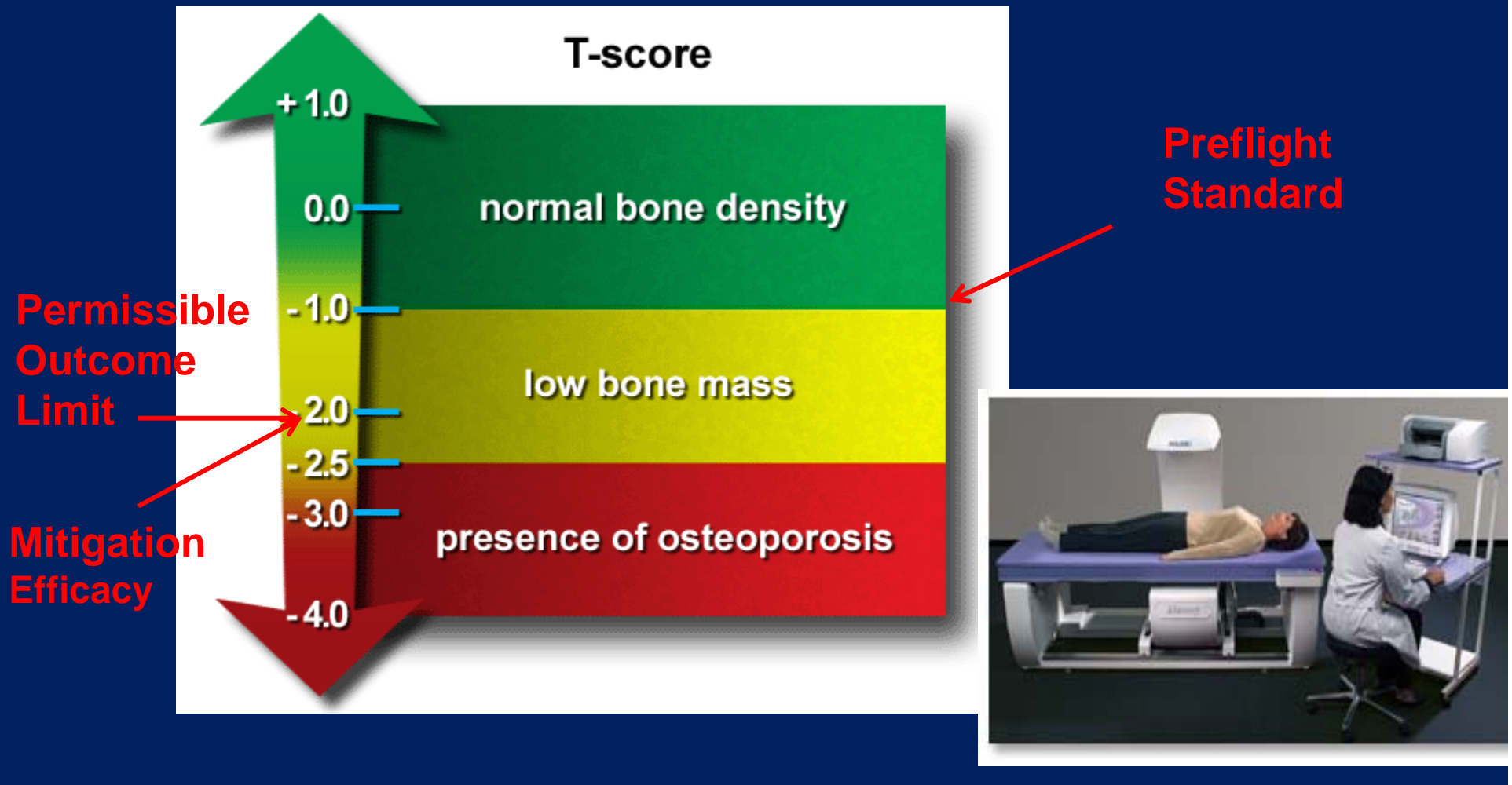


# Increased risk in astronauts?

## Limited time to count incidence of fractures.

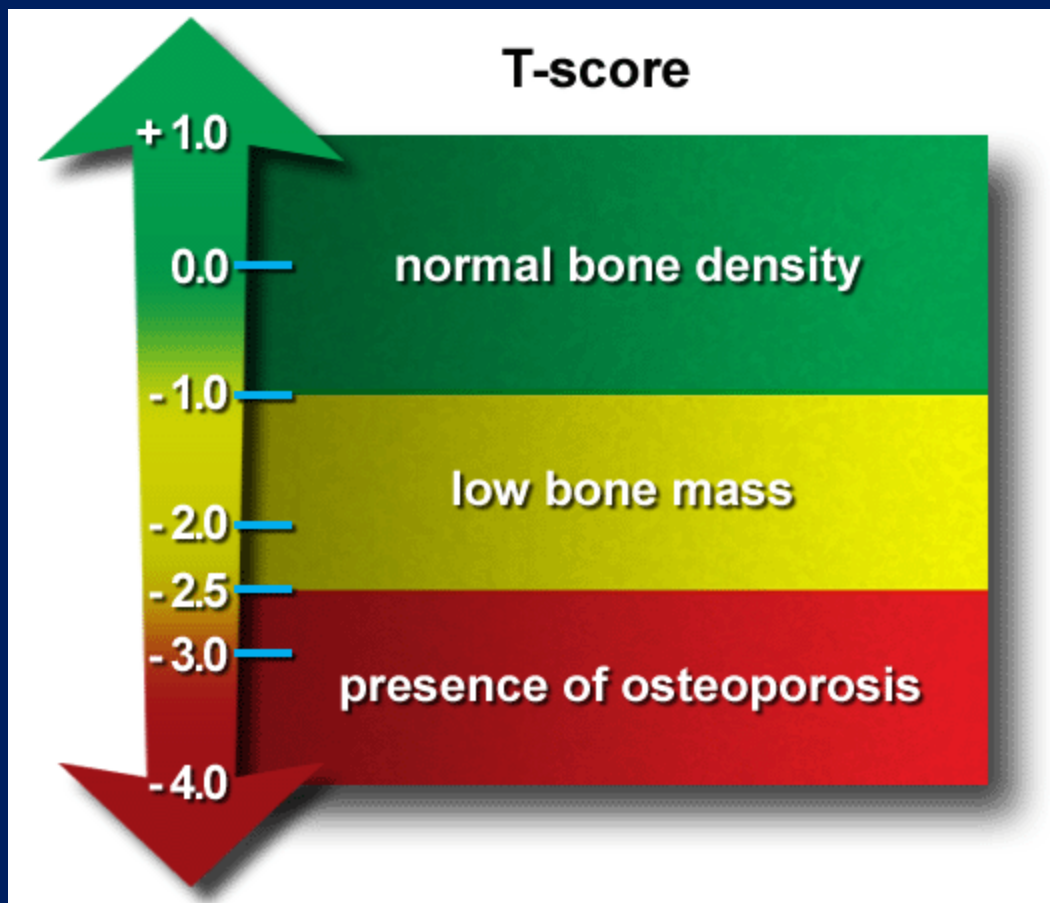


**NASA measures Bone Mineral Density [BMD]  
by DXA as a surrogate for fracture just as clinical  
world. –T-scores (Not BMD change). circa 2000**



“Osteoporosis is a skeletal disorder characterized by ***compromised bone strength*** predisposing to an increased risk of fracture. Bone strength reflects the integration of two main features: bone density and bone quality.”

JAMA. 2001



Disconnects evident  
In population studies.

FRACTURE CASES

NON FRACTURES

Widely-applied surrogate for fracture

**BONE STRENGTH IS  
INFLUENCED BY ADDITIONAL  
FACTORS THAT ARE NOT  
MEASURED BY DXA AREAL  
BMD.**

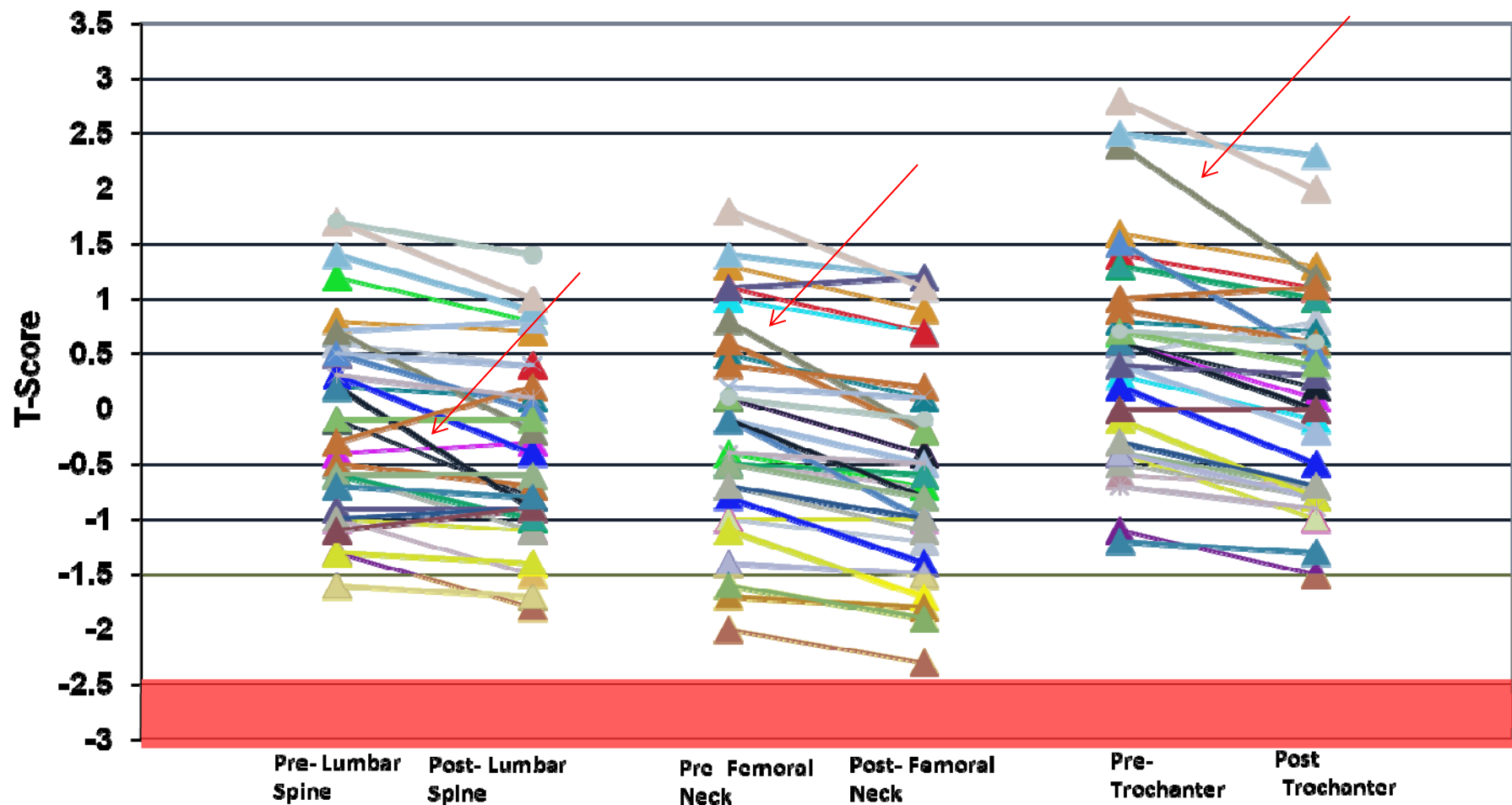


# Diagnostic Guidelines Not Meaningful for Astronauts

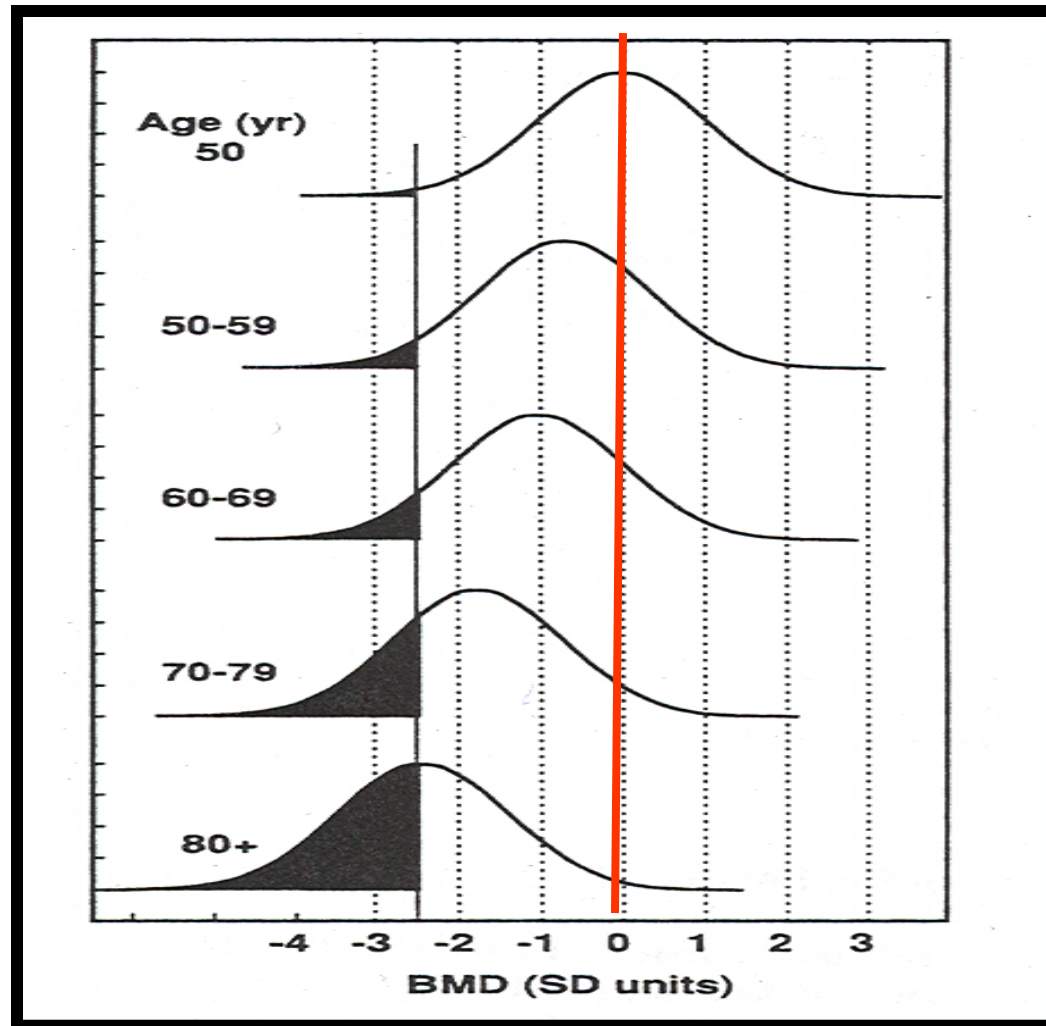
for peri- and postmenopausal women and men > 50 years.

**BMD T-Score Values\* Expeditions 1-25 (n=33)**

**\*Comparison to Population Normals**



Age is important risk factor for bone loss but the utility for < 50 years not clearly evident .\*

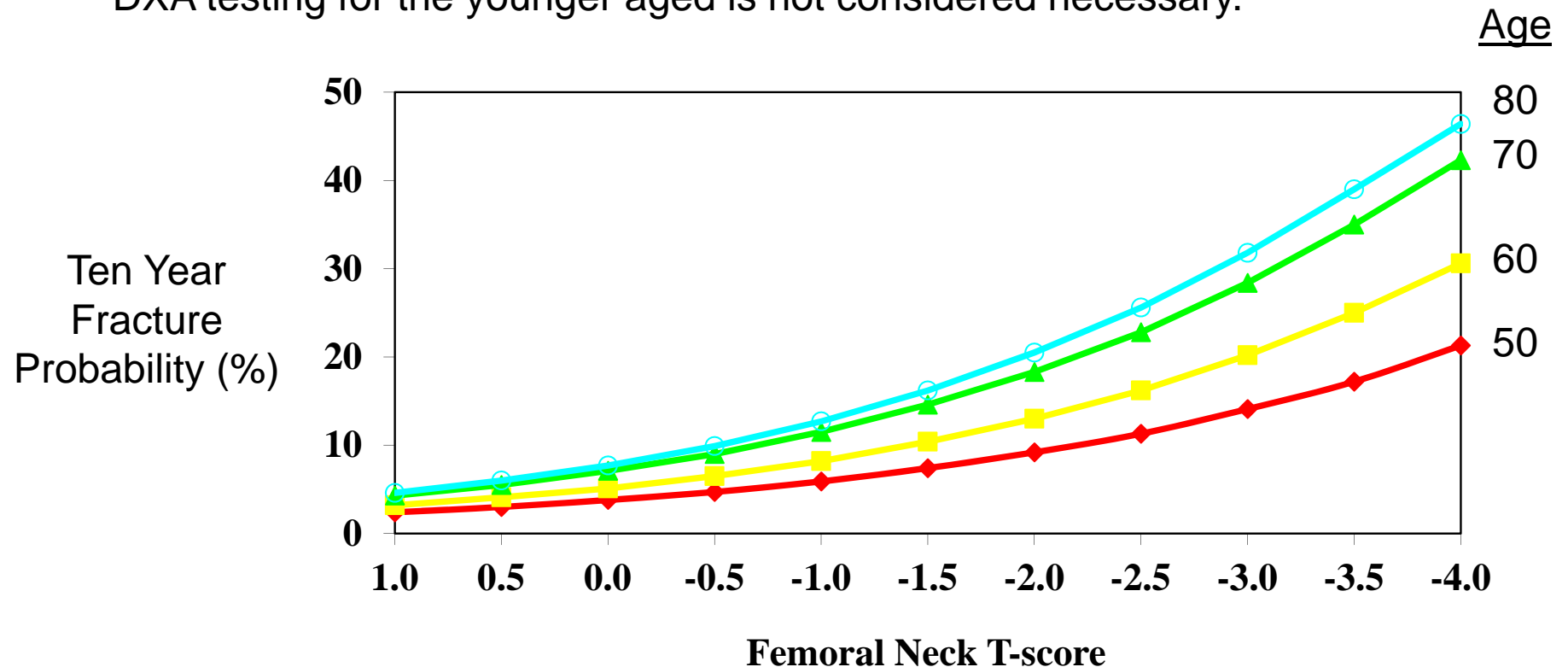


Kanis et al JBMR 9(8):1137, 1994

\* The use of DXA BMD for surveillance of active astronauts is a unique application.

# Risk for osteoporotic fractures is lower at younger ages.

Given the probability of fracture drives the requirement for interventions, DXA testing for the younger aged is not considered necessary.



Probability of first fracture of hip, distal forearm, proximal humerus, and symptomatic vertebral fracture in women of Malmö, Sweden.

Adapted from:  
Kanis JA et al. *Osteoporosis Int.* 2001;12:989-995  
Slide Courtesy of S. Petak, MD.

Uncertainty exists. Are the long-duration astronauts at risk?

**WHAT COULD BE MEASURED  
TO DEFINE A RARE RISK IN  
YOUNGER PERSONS?**

# History of Bone Imaging in Space

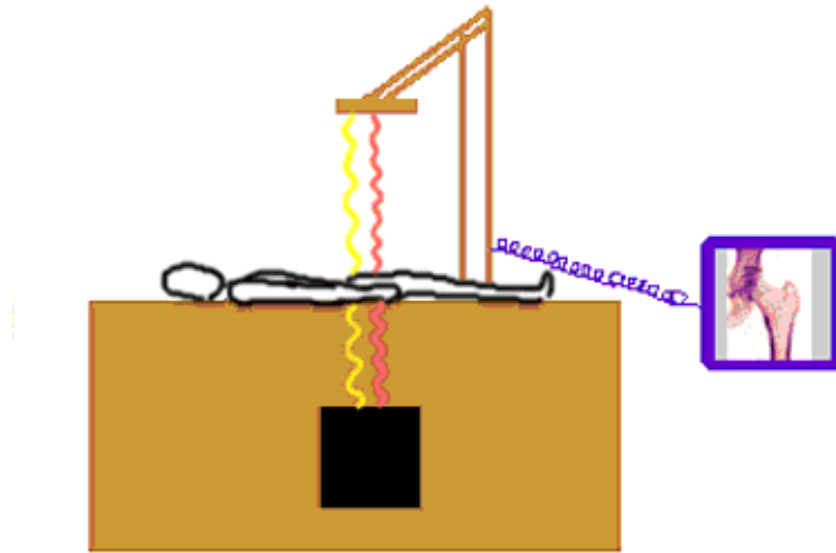
Gemini			Space Shuttle	
Mercury	Apollo	Skylab		ISS
1961-63	1965-66	1968-72	1973-74	2000-present
	<ul style="list-style-type: none"> <li>• X-ray densitometry</li> </ul>	<ul style="list-style-type: none"> <li>• SPA heel and wrist</li> </ul>	<ul style="list-style-type: none"> <li>• SPA heel and wrist</li> </ul>	<ul style="list-style-type: none"> <li>• DXA</li> <li>• QCT</li> <li>• <i>HR3DpQCT (ESA)</i></li> </ul>
		Soyuz/Salyut	Mir	
		1974-85	1974-85	
		<ul style="list-style-type: none"> <li>• SPA</li> <li>• DPA</li> </ul>	<ul style="list-style-type: none"> <li>• DXA whole body</li> <li>• CT of lumbar spine BMD</li> </ul>	



Slide courtesy of S. Amin, adapted from Dr. Jean Sibonga, NASA JSC



# Dual-energy X-ray Absorptiometry-DXA



Measurement of bone mineral in 2-d **projection** of bone [ $BMD_a$ ]  $g/cm^2$

- Improved precision; Low radiation; Shorter scan times; BMD measures over multiple skeletal sites
- Validated in numerous population studies for fracture prediction
- Long established, widely-applied **surrogate** for fracture outcome – become NASA standards, but T-scores give only Relative Risks

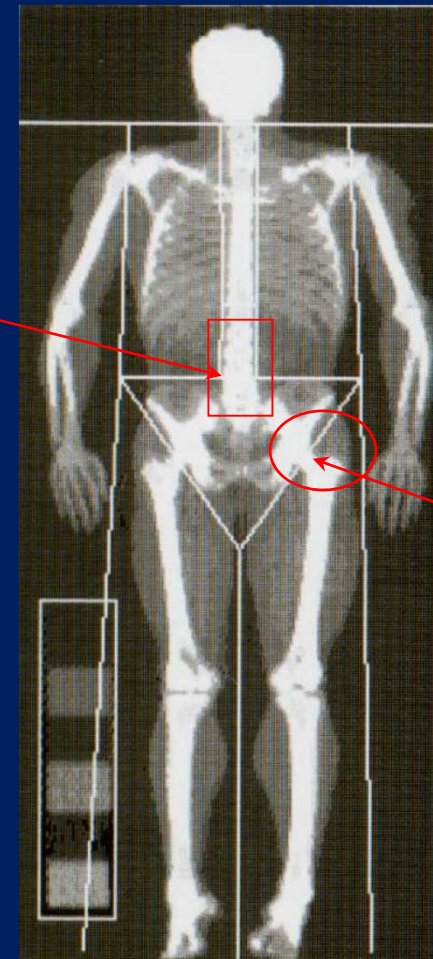
# DXA: BMD losses are **site-specific** and **rapid**

vs. 0.5 – 1.0 % BMD **loss/year** in the aged

Areal BMD g/cm <sup>2</sup>	%/Month Change $\pm$ SD
Lumbar Spine	-1.06 $\pm$ 0.63*
Femoral Neck	-1.15 $\pm$ 0.84*
Trochanter	-1.56 $\pm$ 0.99*
Total Body	-0.35 $\pm$ 0.25*
Pelvis	-1.35 $\pm$ 0.54*
Arm	-0.04 $\pm$ 0.88
Leg	-0.34 $\pm$ 0.33*
*p<0.01, n=16-18	

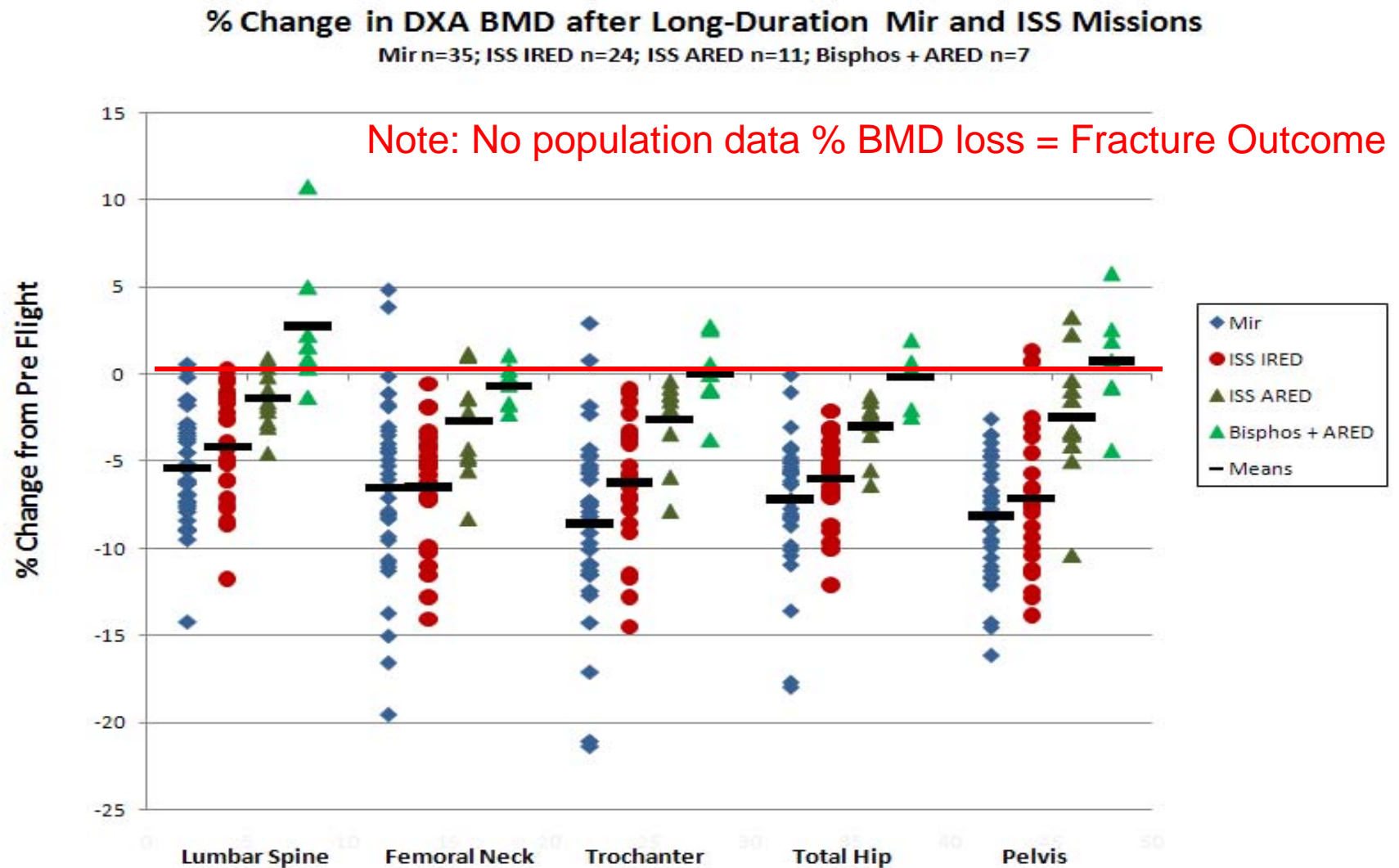
**Whole Body**  
0.3% / month

**Lumbar Spine**  
1% / month



**Hip**  
1.5% / month

# Effects of exercise regimens described using DXA BMD



1217

\* Updated data since 2010 Bone Summit

## **A Limitation: DXA Cannot distinguish changes in bone geometry– a contributor to bone strength.**

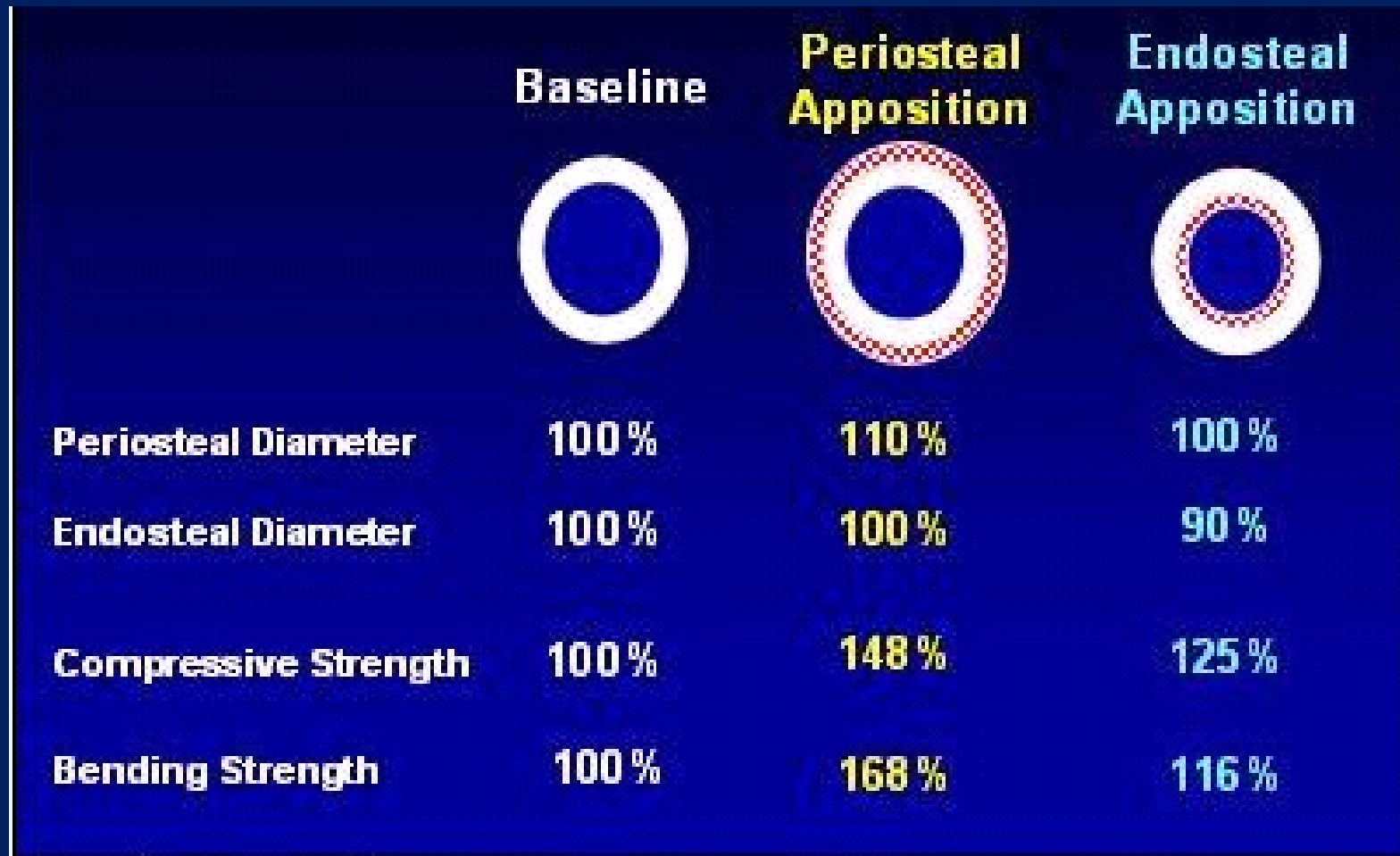
### **Effect of geometry on long bone strength**

			
<b>aBMD</b> <u>Areal</u> (g/cm <sup>2</sup> )	<b>1</b>	<b>1</b>	<b>1</b>
<b>Compressive Strength</b>	<b>1</b>	<b>1.7</b>	<b>2.3</b>
<b>Bending Strength</b>	<b>1</b>	<b>4</b>	<b>8</b>

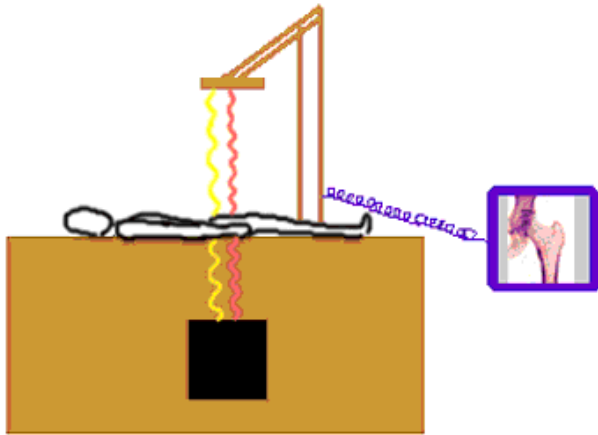
# Exercise changes geometry of whole bone (adult skeleton)- not detected by DXA.

1. Haapasalo H, Sievanen H, Kannus P, Heinonen A, Oja P, Vuori I. 1996 **Dimensions and estimated mechanical characteristics of the humerus after long-term tennis loading.** J Bone Miner Res. 11:864-872.
2. Adami S, Gatto D, Braga V, Bianchini D, Rossini M. 1999 **Site-specific effects of strength training on bone structure and geometry of ultradistal radius in postmenopausal women.** J Bone Miner Res. 14(1):120-124.
3. Haapasalo H, Kontulainen S, Sievanen H, Kannus P, Jarvinen M, Vuori I. 2000 **Exercise-induced bone gain is due to enlargement in bone size without a change in volumetric bone density: a peripheral quantitative computed tomography study of the upper arms of male tennis players.** Bone 17(3):351-357.
4. Vainionpaa A, Korpelainen R, Sievanen H, Vihriaia E, Leppaluoto J, Jamasa T. 2007 **Effect of impact exercise and its intensity on bone geometry at weight-bearing tibia and femur.** Bone 40(3):604-611.
5. Hind K, Gannon L, Whatley, Cooke C, Truscott J. 2011 **Bone cross-sectional geometry in male runners, gymnasts, swimmers and non-athletic controls: a hip-structural analysis study.** Eur J Appl Physiol . e pub May 24

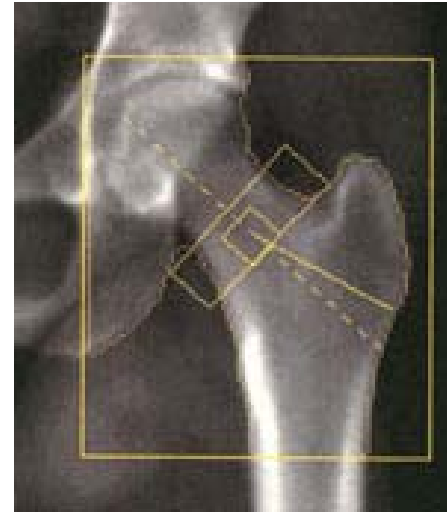
## The *location* of formed bone makes a difference.



# Densitometry & Reported Measurement



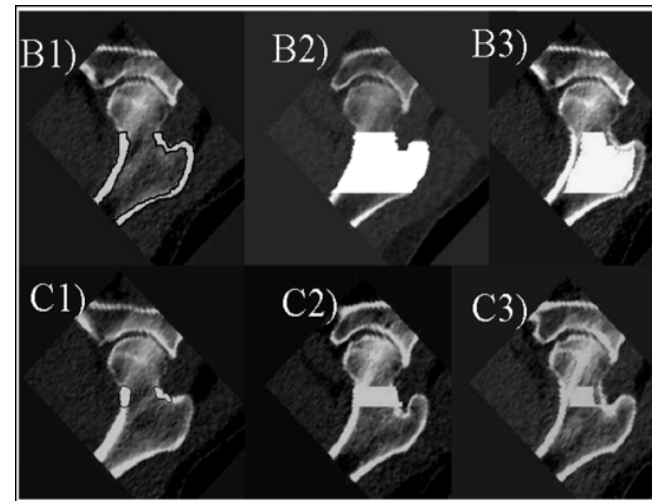
DXA reports areal BMD (aBMD)



**g/cm<sup>2</sup>** averaged for cortical + trabecular bone

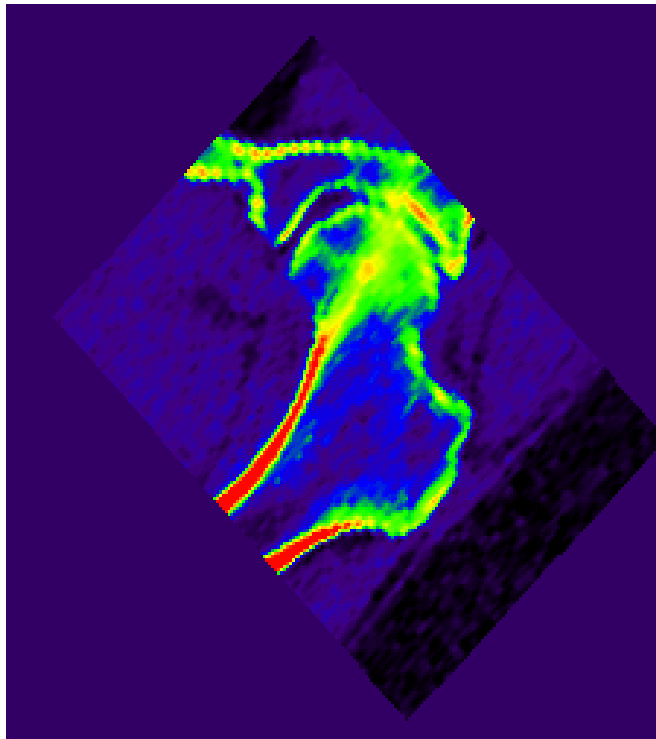


QCT quantifies volumetric BMD



**g/cm<sup>3</sup>** for separate cortical & trabecular bone

# Research: QCT detects different rate of vBMD loss in separate bone compartments of hip. (n=16 ISS volunteers)



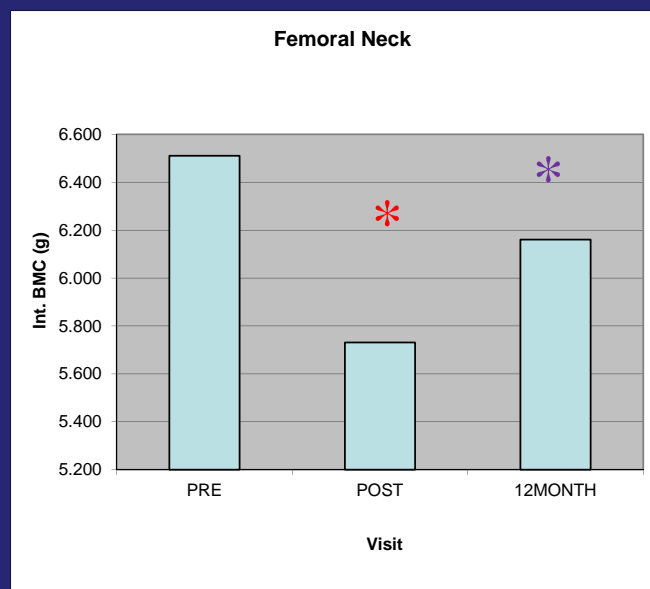
Index DXA	%/Month Change $\pm$ SD	Index QCT	%/Month Change $\pm$ SD
aBMD Lumbar Spine	1.06 $\pm$ 0.63*	Integral vBMD Lumbar Spine	0.9 $\pm$ 0.5
		Trabecular vBMD Lumbar Spine	0.7 $\pm$ 0.6
aBMD Femoral Neck	1.15 $\pm$ 0.84*	Integral vBMD Femoral Neck	1.2 $\pm$ 0.7
		Trabecular vBMD Femoral Neck	2.7 $\pm$ 1.9
aBMD Trochanter	1.56 $\pm$ 0.99*	Integral vBMD Trochanter	1.5 $\pm$ 0.9
*p<0.01, n=16-18		Trabecular vBMD Trochanter	2.2 $\pm$ 0.9

LeBlanc, J Musculoskelet Neuronal Interact. 2000 ;  
Lang , J Bone Miner Res, 2004;



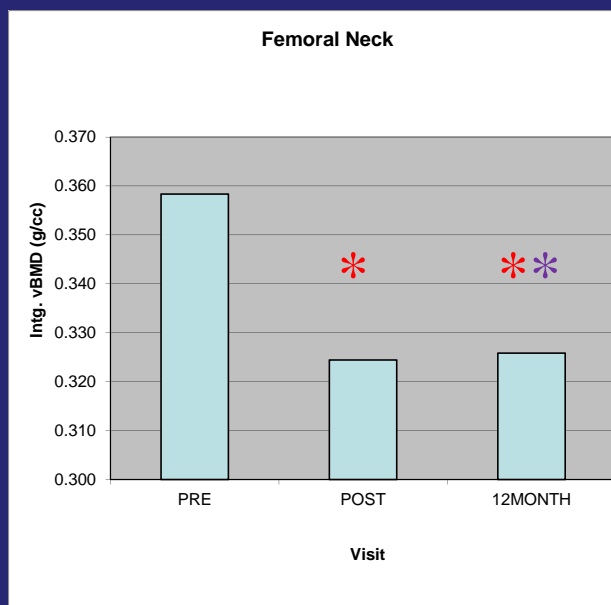
# QCT Postflight – Changes in Femoral Neck structure detected 12 months after return

## Bone Mineral Content (g)



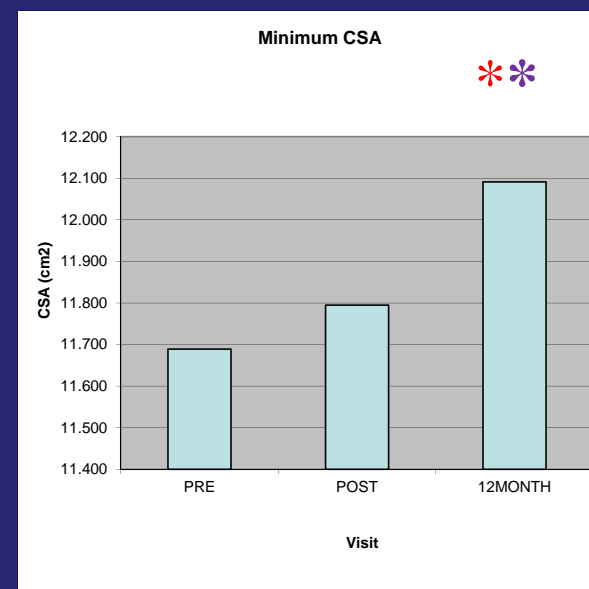
Pre Post 12

## Volumetric Bone Mineral Density g/cm<sup>3</sup>



Pre Post 12

## Minimum Cross-sectional Area cm<sup>2</sup>



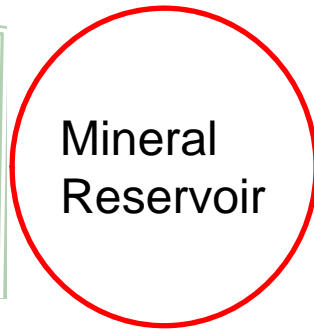
Pre Post 12

$P < 0.05$  with respect to preflight\*, postflight\*

# Two Functions of the Skeleton- increasing understanding by biochemistry

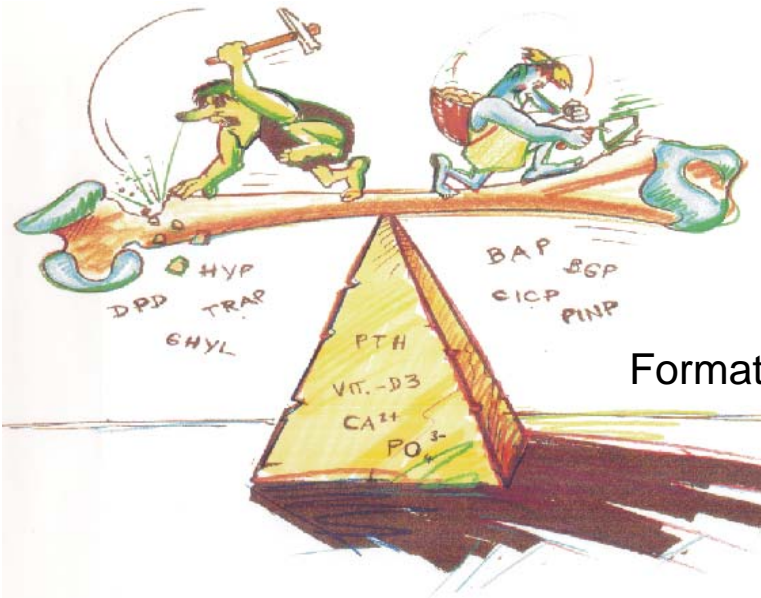


Structural Framework



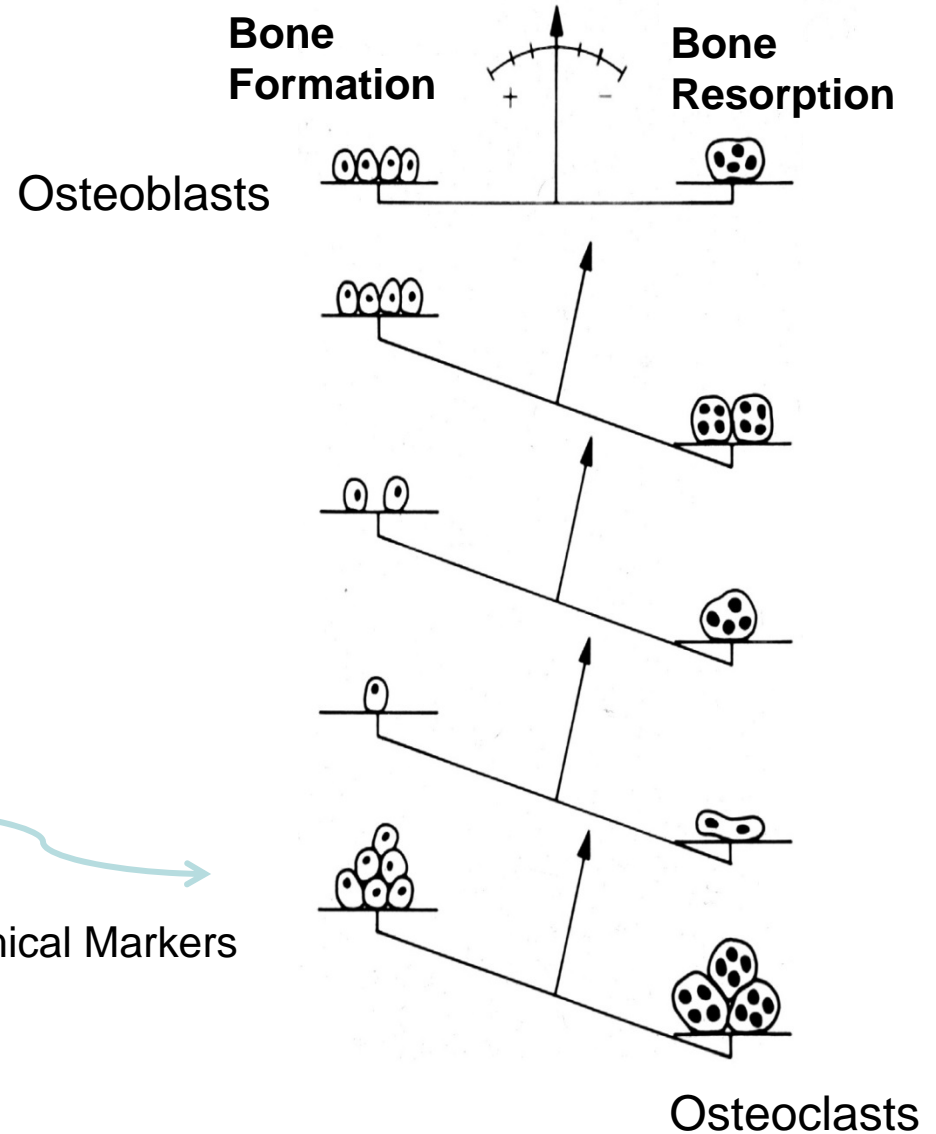
Mineral Reservoir

Resorption Biochemical Markers

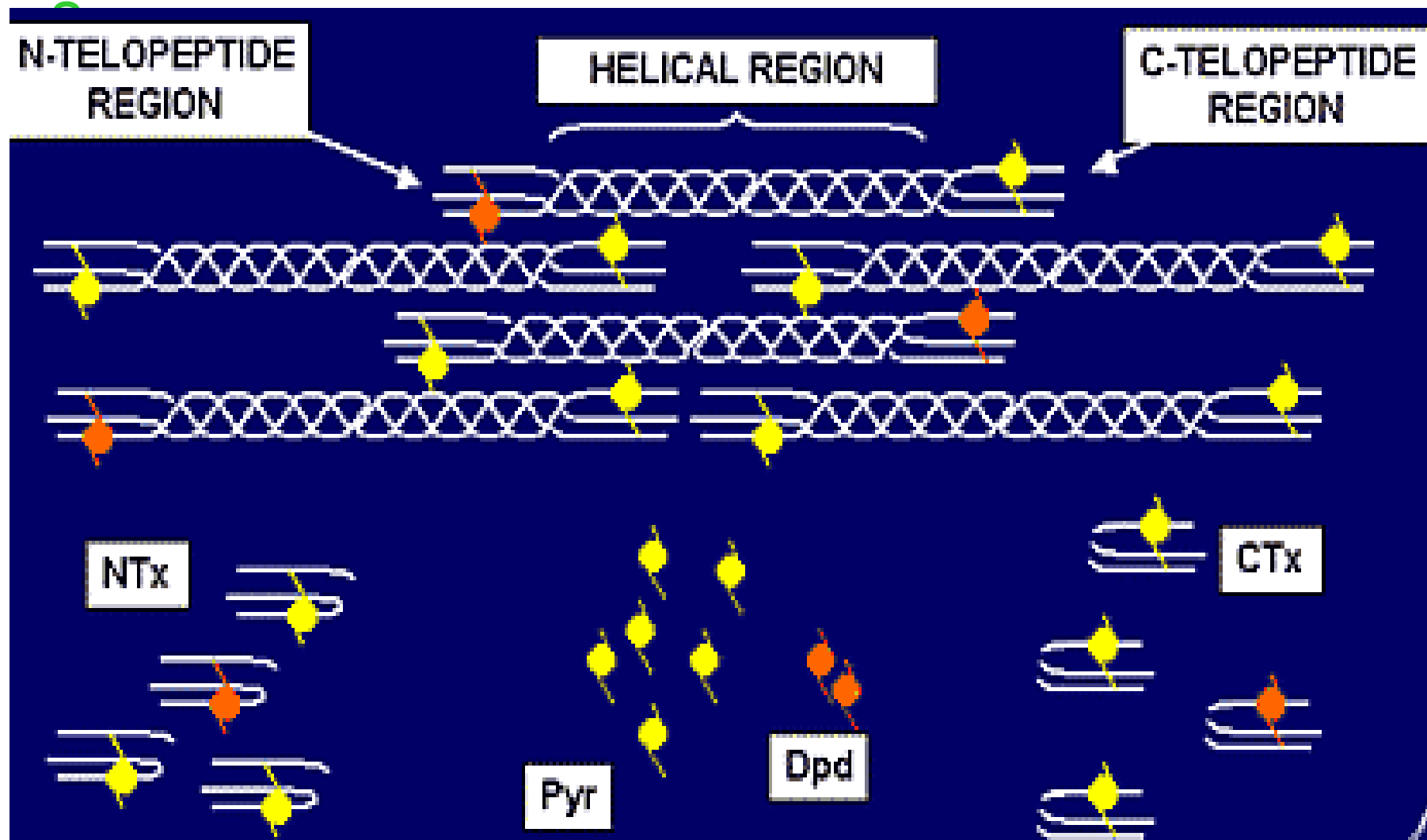


Formation Biochemical Markers

CELLULAR BASIS OF IMBALANCE IN SKELETAL REMODELING

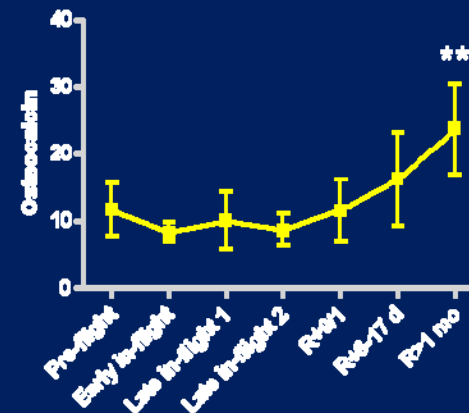
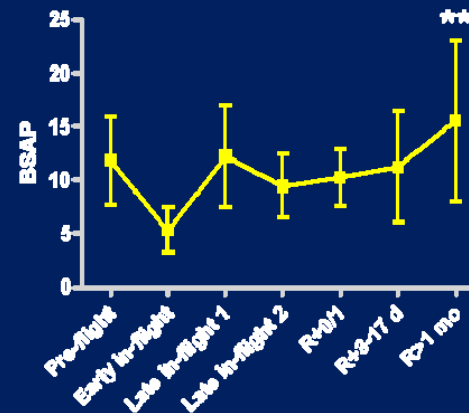
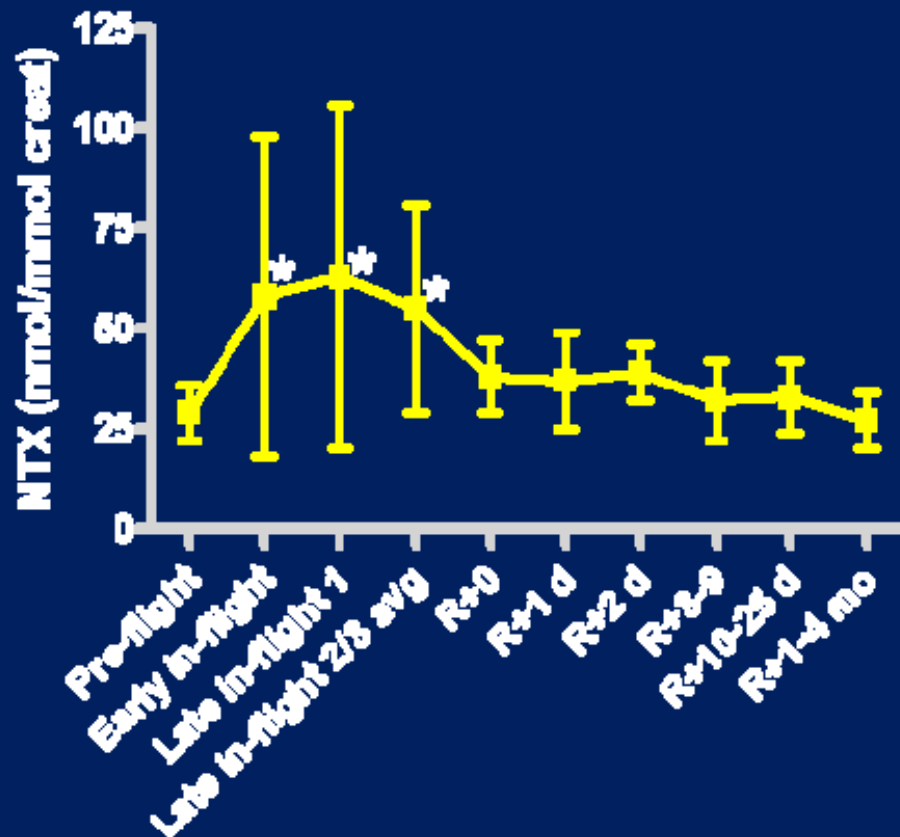


**Serum and urinary biomarkers are by-products of bone turnover and bone cell activity.**



Bone breakdown is increased, formation is uncoupled from resorption, and bone gain and loss are unbalanced\*

Reflects changes in bone cells but not where bone mass is lost.

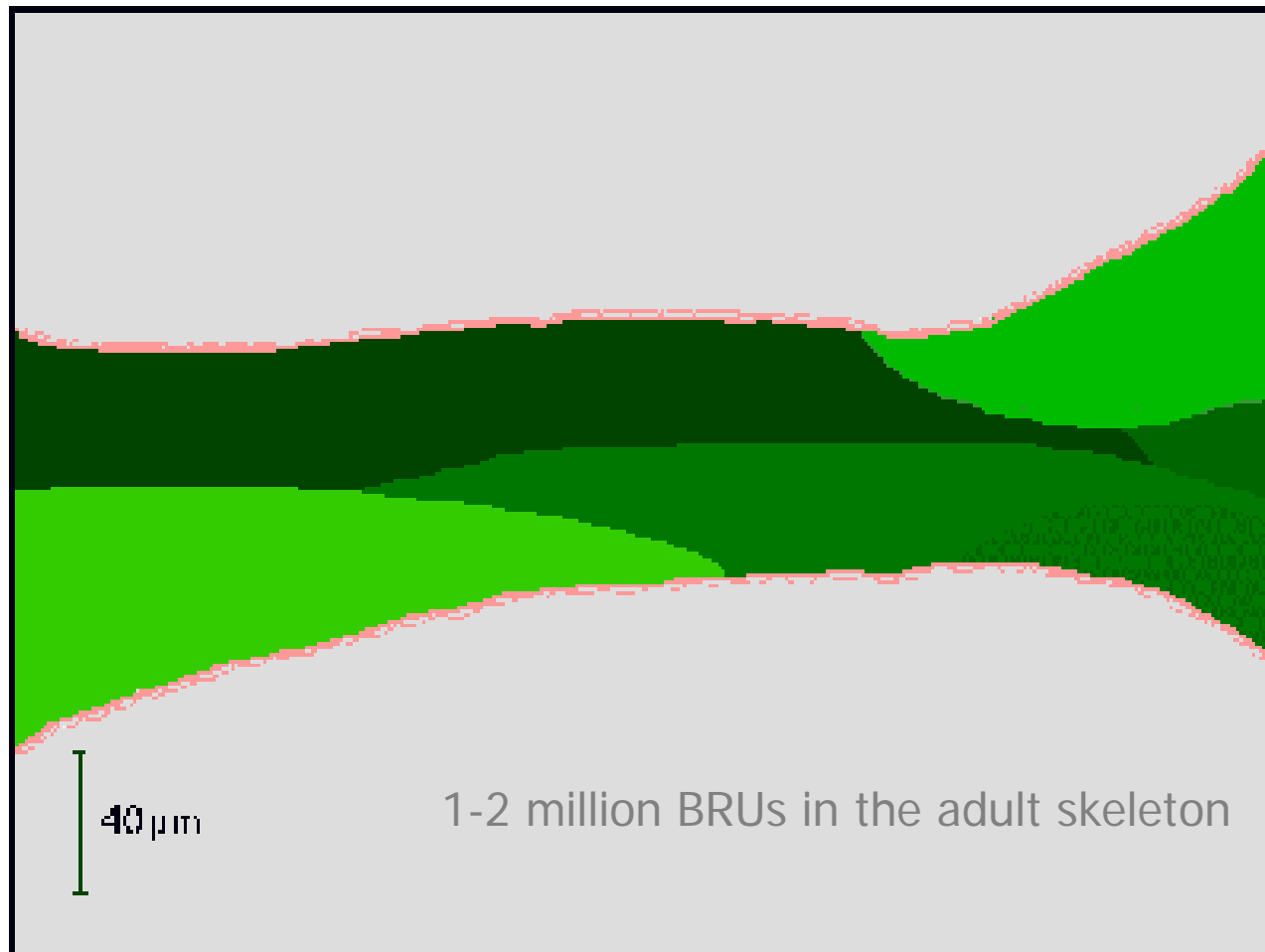


(Smith et al, JBMR 2005); adapted by Sibonga

\* Could lead to net bone loss in skeleton.

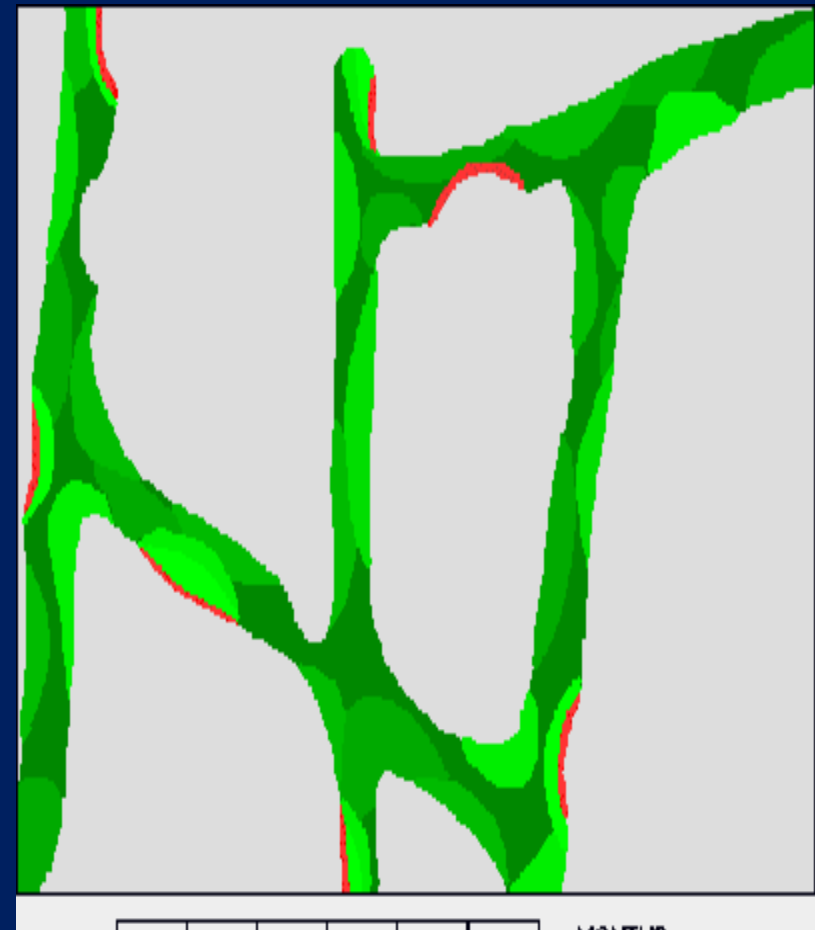
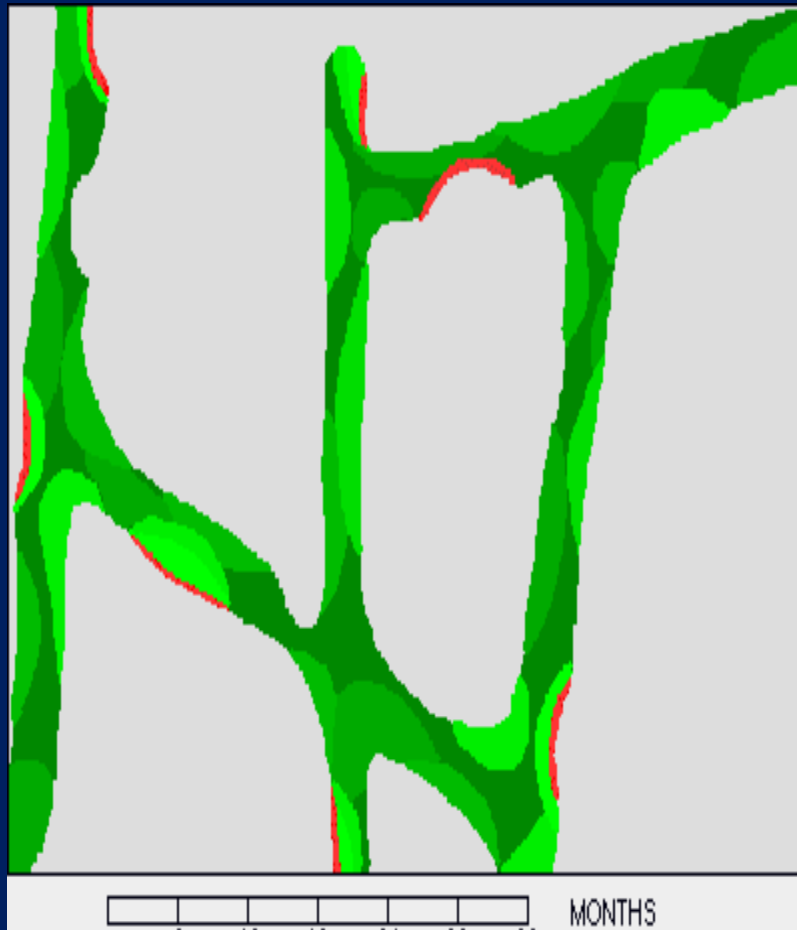
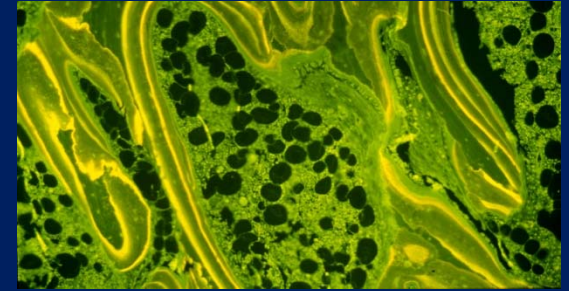
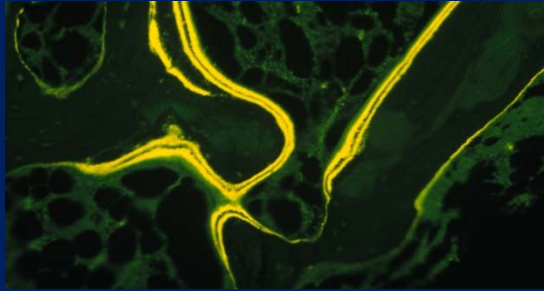
## **HIGHLY-REGULATED** ACTIONS OF BONE CELLS on BONE TURNOVER.

Under-filling, over-filling, balanced filling of the bone remodeling unit [BRU]  
Can impact overall structural strength of whole bone (skeletal region).



Remodeling of bone at the level of a single "BRU"

Some insight gained by comparison to  
Earth-based disorders of increased bone resorption.



**Representative manifestation on bone microarchitecture.  
Clinical test not currently available for hip/spine.**



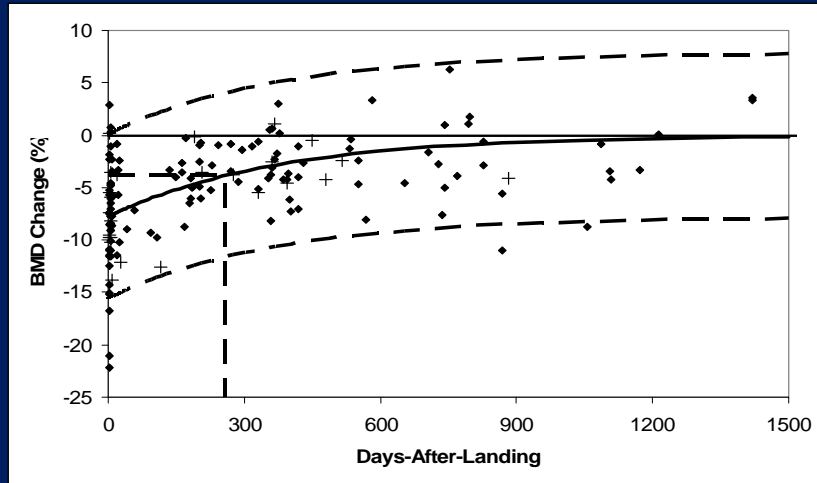
(Mosekilde, 2000; Seeman, 2002; Silva, 1997; Kleerekoper, 1985)

Path to Risk Reduction

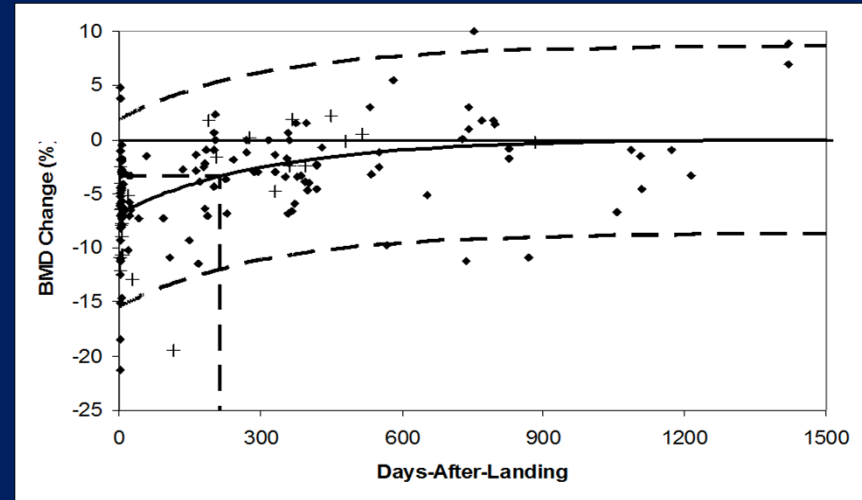
# **HOW CAN RESEARCH DATA BE USED FOR CLINICAL CARE IN THE ABSENCE OF FRACTURE EVIDENCE?**



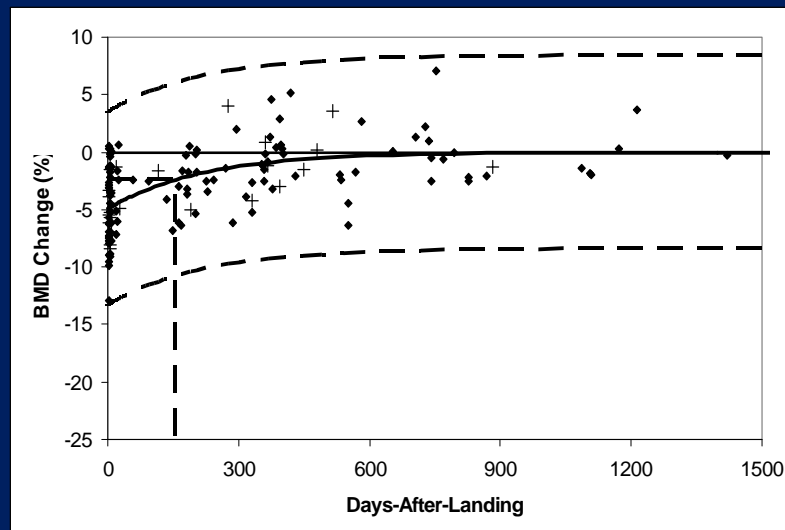
# DXA BMD increases in Postflight – but not sufficient to assess recovery of *bone strength*.



Trochanter

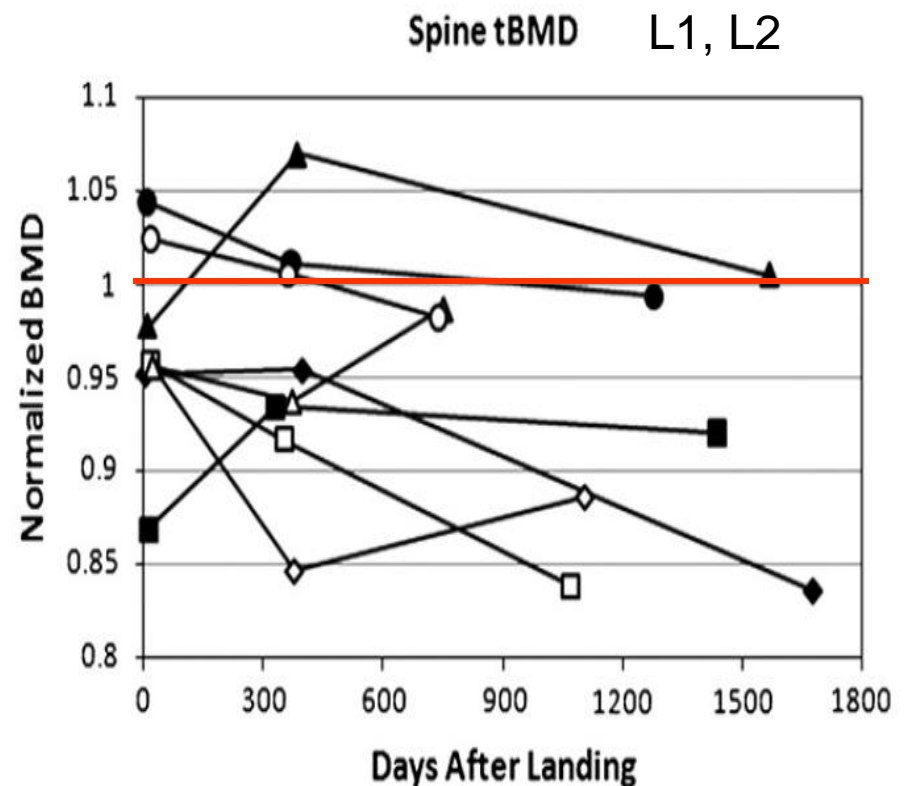
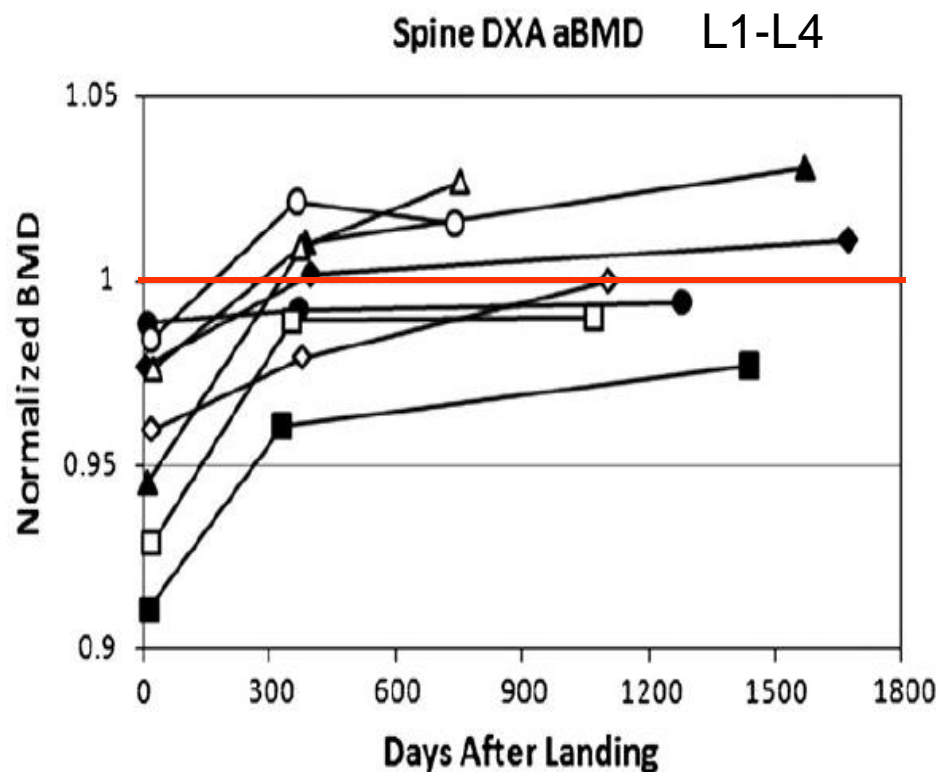


Femoral neck



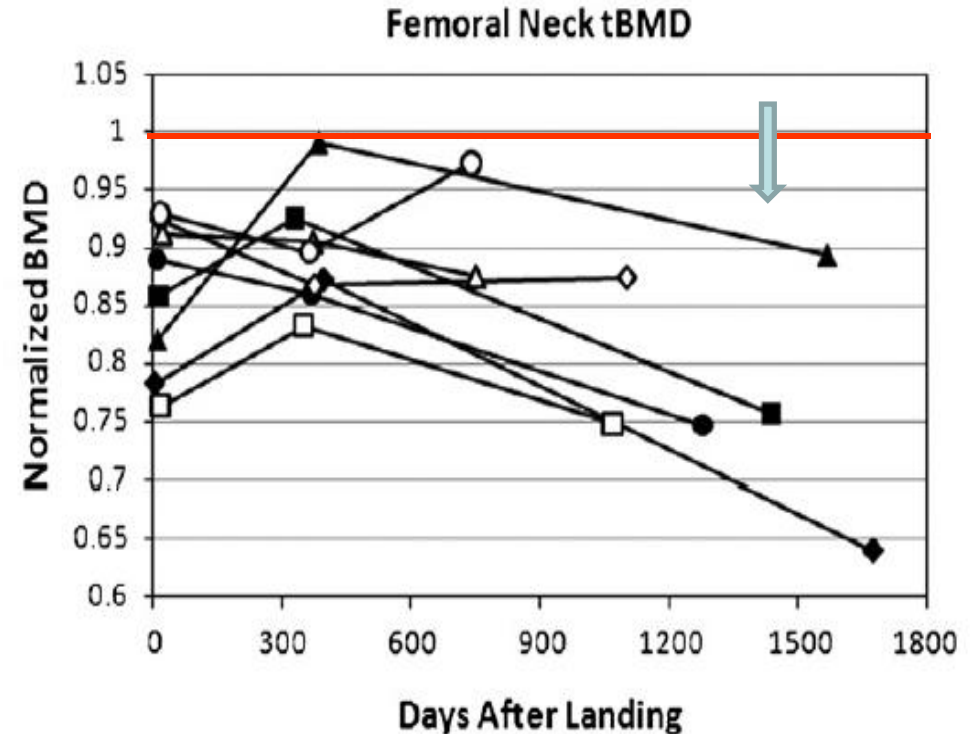
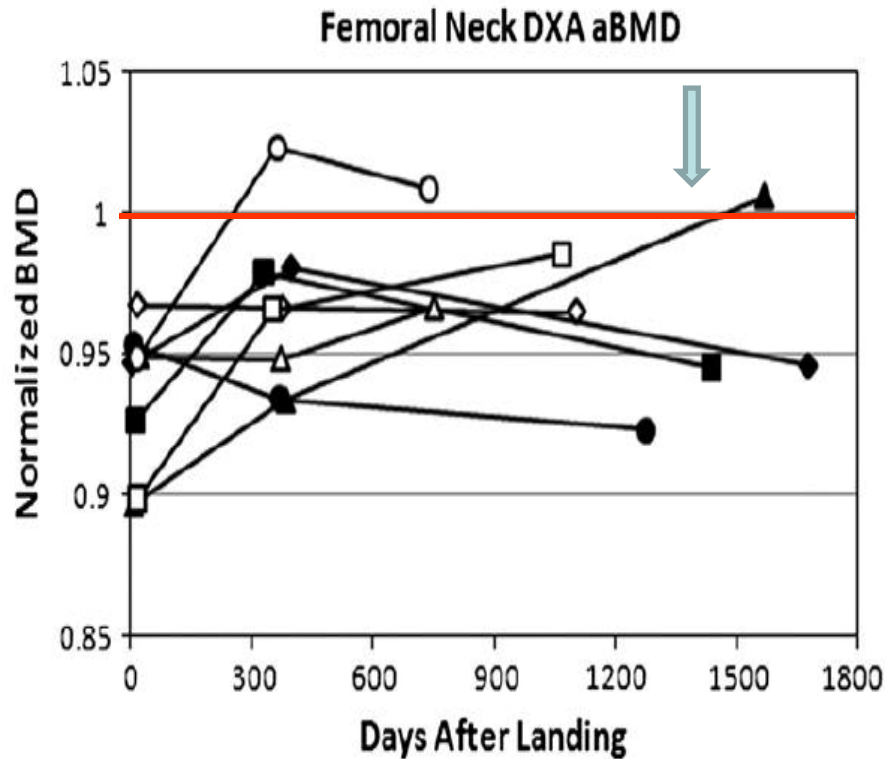
Lumbar Spine

# DXA & QCT Spine in 8 ISS astronauts : Expanding our Understanding of Recovery After Spaceflight



QCT Extension Study (n=8) Postflight Trabecular BMD in hip. Carpenter, D et al. Acta Astronautica, 2010.

# DXA & QCT Femoral Neck



QCT Extension Study (n=8) Postflight Trabecular BMD in hip. Carpenter, D et al. Acta Astronautica, 2010.

# Clinical Evidence: QCT measures are independent predictors of hip fracture to supplement aBMD.

JOURNAL OF BONE AND MINERAL RESEARCH  
Volume 23, Number 8, 2008  
Published online on March 17, 2008; doi: 10.1359/JBMR.080316  
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## Proximal Femoral Structure and the Prediction of Hip Fracture in Men: A Large Prospective Study Using QCT\*

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[Abstract](#) | [Full Article \(HTML\)](#) | [References](#) | [Supporting Information](#)  
Cited By

NASA Johnson Space Center

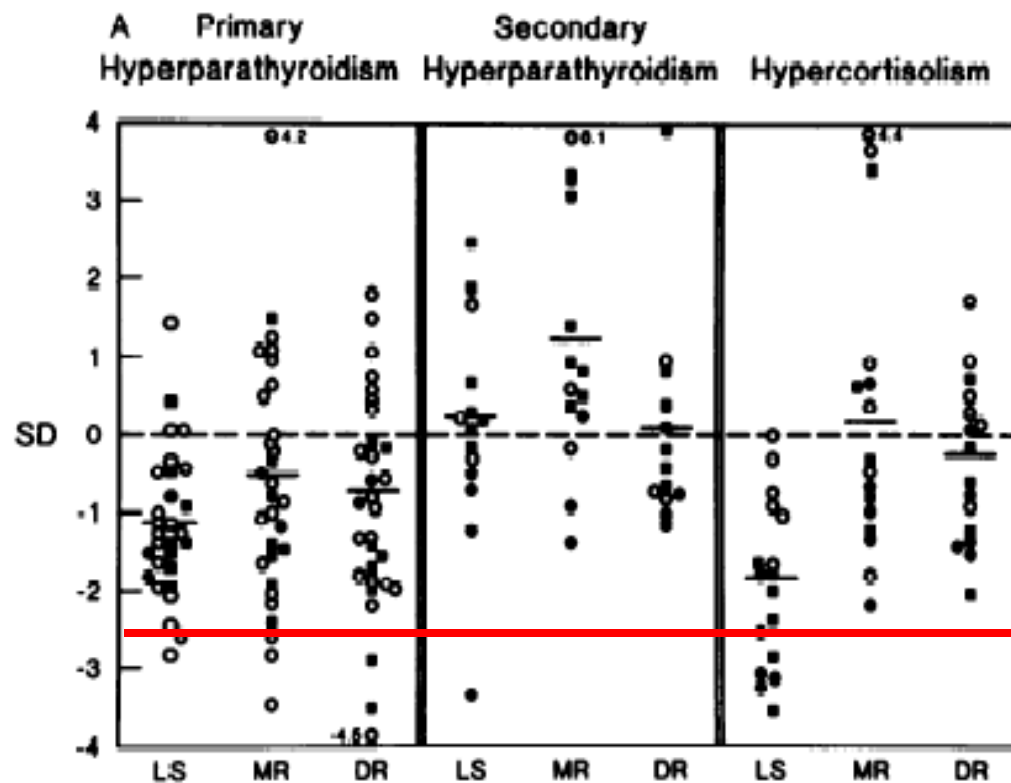
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## In Vivo Discrimination of Hip Fracture With Quantitative Computed Tomography: Results From the Prospective European Femur Fracture Study (EFFECT)

Valérie Danielle Bousson,<sup>1,2</sup> Judith Adams,<sup>3</sup> Klaus Engelke,<sup>4</sup> Mounir Aout,<sup>5</sup> Martine Cohen-Solal,<sup>6</sup> Catherine Bergot,<sup>2</sup> Didier Haguénauer,<sup>7</sup> Daniele Goldberg,<sup>8</sup> Karine Champion,<sup>9</sup> Redha Aksouh,<sup>1</sup> Eric Vicaud,<sup>5</sup> and Jean-Denis Laredo<sup>1,2</sup>

# DXA BMD not as good of predictor of hip fractures for the “complicated patient” i.e., non-age-related bone loss

- Different patterns of bone “loss” (cortical vs. trabecular) with different metabolic disorders ...analogous to spaceflight effects



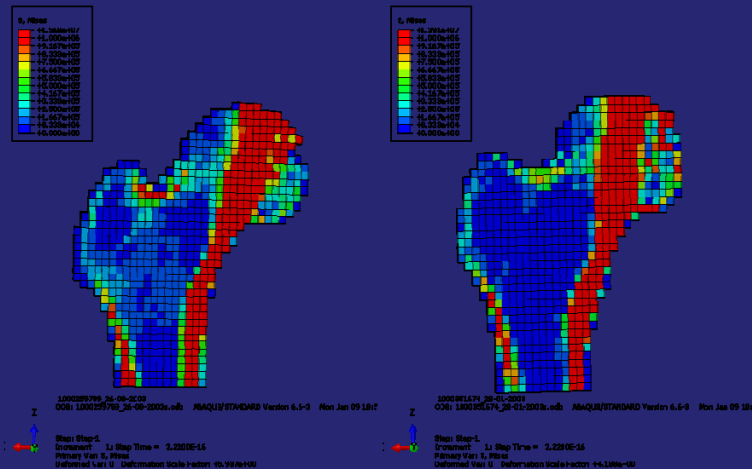
*Seeman, JCI 1992*  
*Slide courtesy of*  
*Dr. Amin, MD*  
Dual Photon  
Absorptiometry (DPA)

# Describing changes in hip bone strength with Finite Element Modeling/Analysis:

## Emerging data from population studies.

- **Male-female differences in prediction of hip fracture during finite element analysis.** Keyak JH, Sigurdsson S, Karlsdottir G, Oskarsdottir D, Sigmarsdottir A, Zhao S, Kornak J, Harris TB, Sigurdsson G, Jonsson BY, Siggeirsdottir K, Eiriksdottir G, Gudnason V, Lang TR. Bone. 2011;48(6):1239-1245.
- **Association of hip strength estimates by finite –element analysis with fractures in women and men.** Amin S,, Kopperdahl DL, Melton LJ 3<sup>rd</sup>, Achenbach SJ, Therneau TM, Riggs BL, Keaveny TM, Khosla S. J Bone Miner Res. 2011;26(7):1593-1600.
- **Age-dependence of femoral strength in white women and men.** Keaveny TM, Kopperdahl DL, Melton III LJ, Hoffmann PF, Amin S, Riggs BL, Khosla S. J Bone Miner Res. 2010;25(5):994-1001.
- **Osteoporotic Fractures in Med Study Group. Finite element analysis of the proximal femur and hip fracture risk in older men.** Orwoll ES, Marshall LM, Nielson CM, Cummings SR, Lapidus J, Cauley JA, Ensrud K, Lane N, Hoffmann PR, Kopperdahl DL, Keaveny TM J Bone Miner Res. 2009;24(3):475–483.

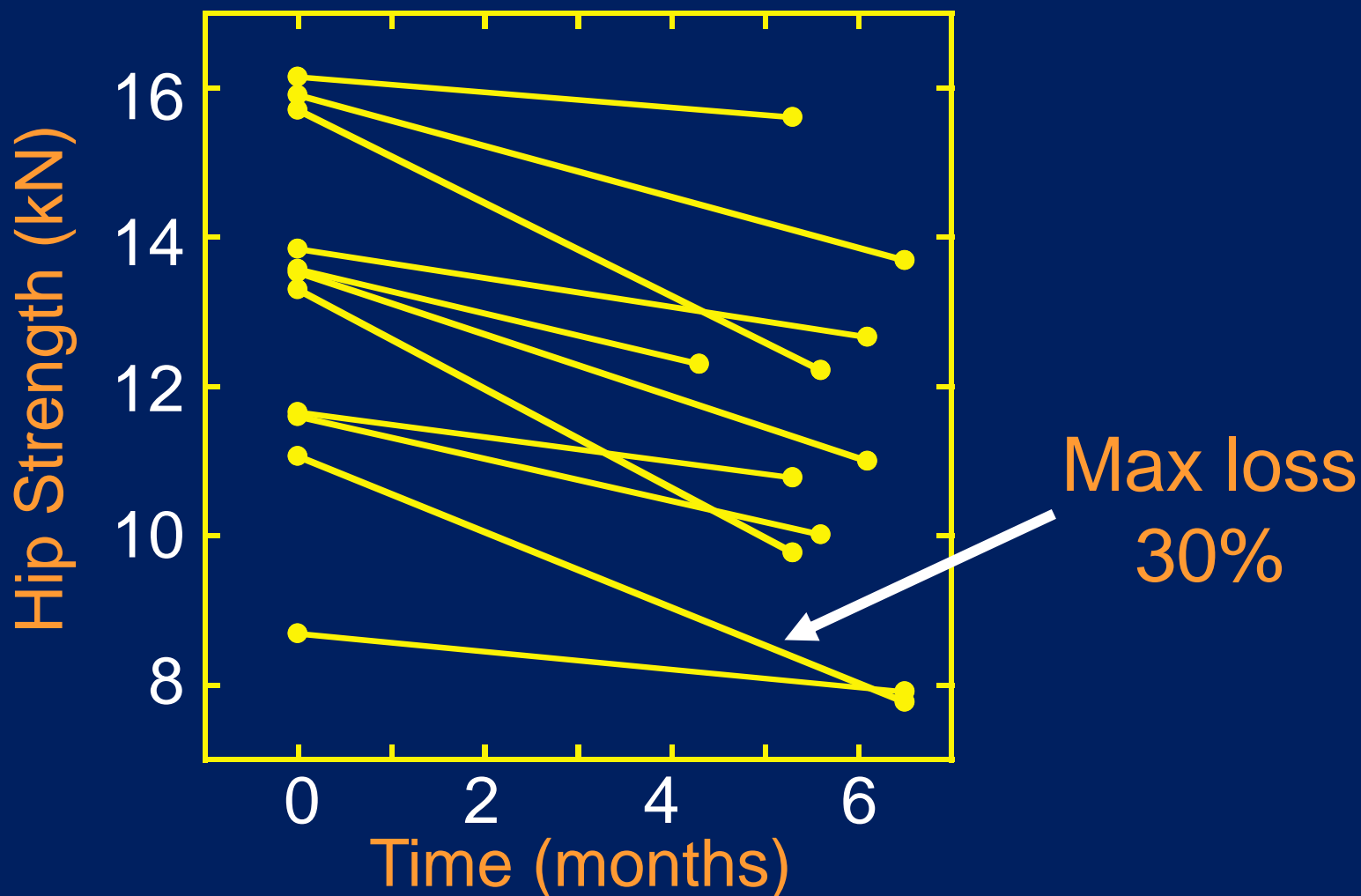
Finite Element Models of QCT data – “FE modeling” is a computational tool to estimate failure loads (“strength”) of complex structures.





# Individual Results

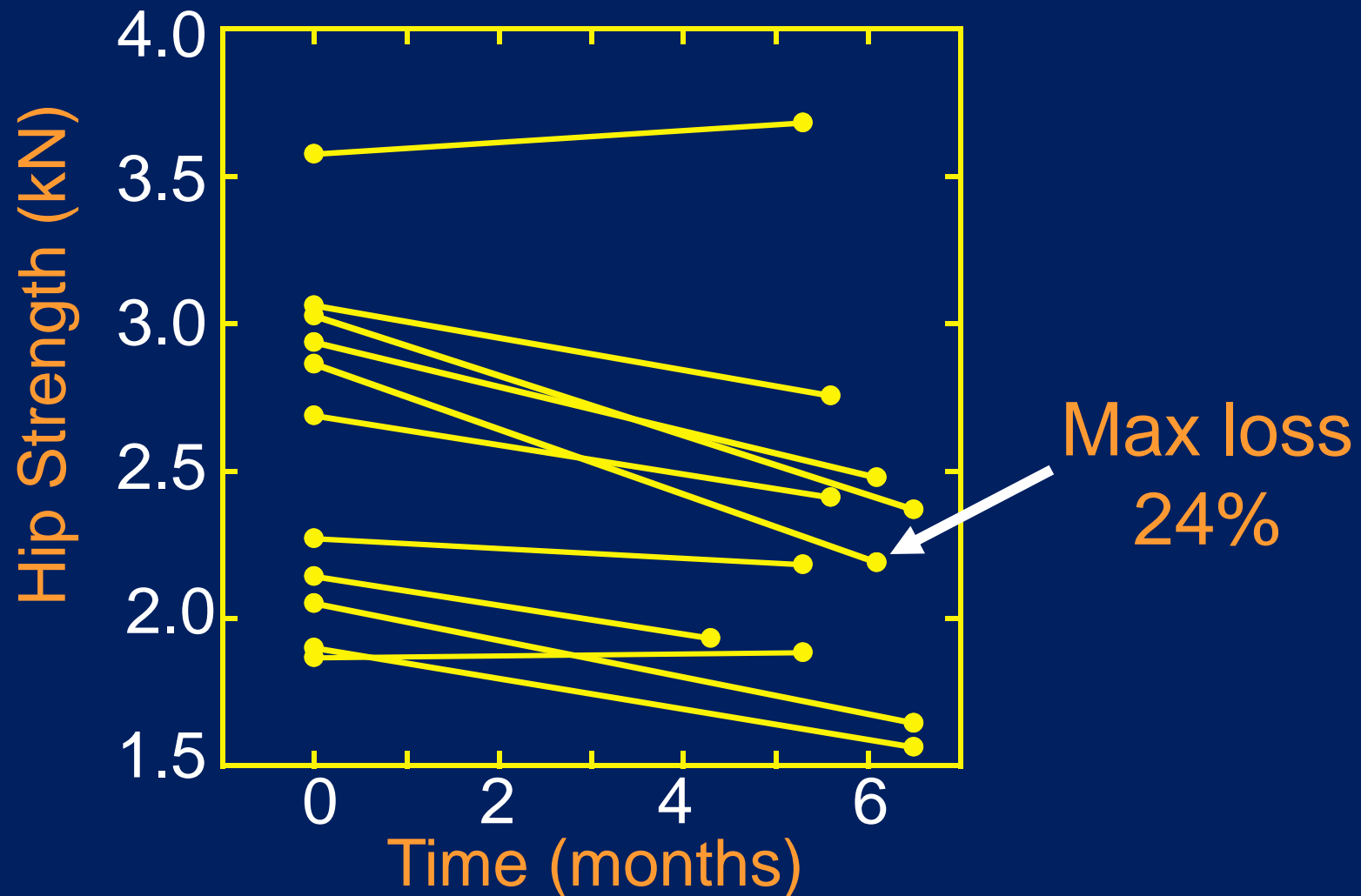
Stance Loading (4 to 30% loss in strength)





# Individual Results

**Fall Loading** (3 gain to 24% loss in strength)

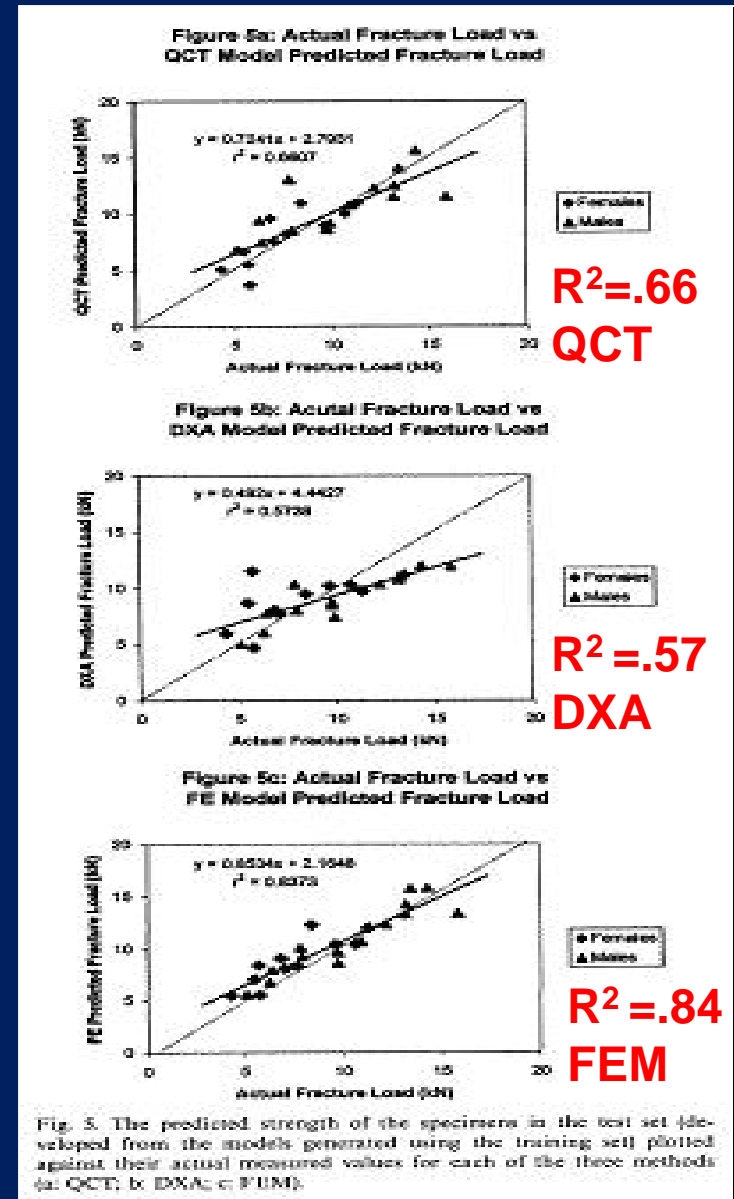


# QCT + FEM has superior capabilities for estimating mechanical strength of ex-vivo specimens.

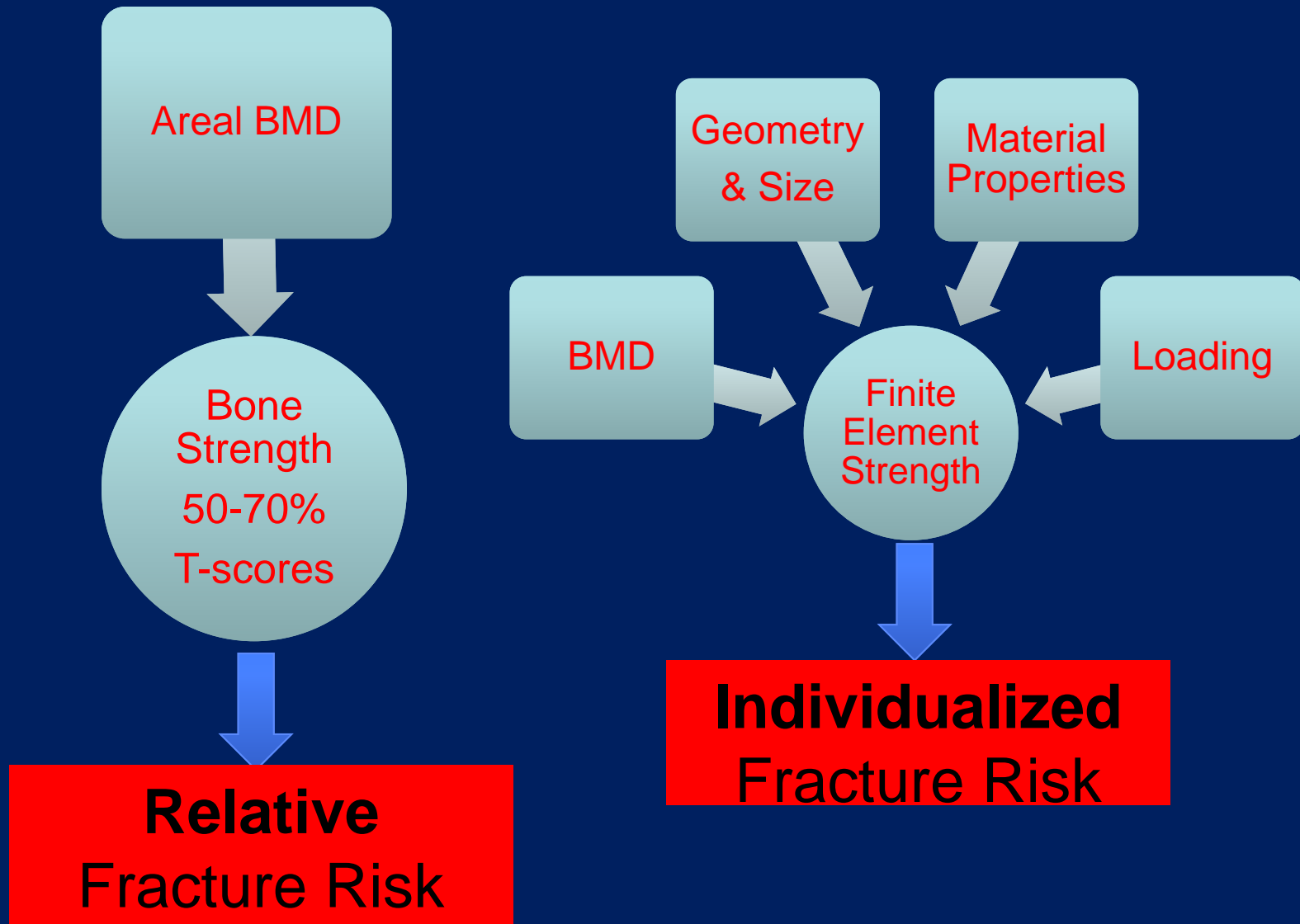
QCT estimates fracture loads better than DXA

QCT + FEM has superior capabilities for estimating fracture loads

DD Cody: Femoral strength is better predicted by finite element models than QCT and DXA. J Biomechanics 32:1013 1999



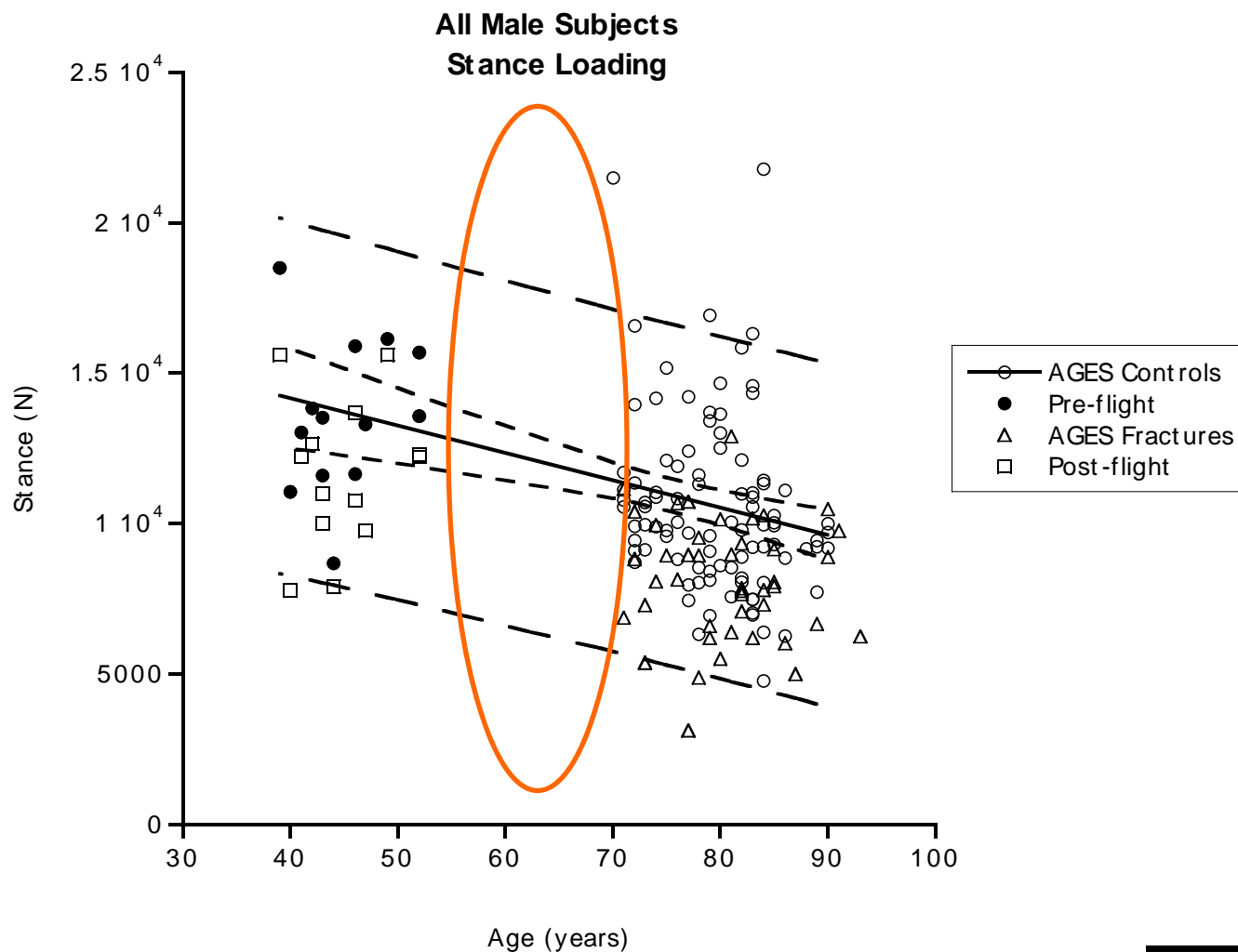
# Assessing Fracture risk following spaceflight by 1 measure vs > 1 measure.



# ***Additional cut-points for Bone Health: FE Modeling of QCT Scans from Population Studies***

## **FE Task Group:**

E. Orwoll MD, S Khosla MD, S Amin MD, T Lang PhD, J Keyak PhD, T Keaveny PhD, D Cody PhD, JD Sibonga, Ph.D.



REPRESENTATIVE POPULATION DATA

Data slide courtesy of Keyak.

# Probabilistic Risk Assessments for Bone Fracture: NASA's Model for Fracture Likelihood

**Biomechanics and Mission Operations**



**Bone Loss in Space**



**Estimate of Fracture Probability**

Probability of Fracture

Probability of event

Probability bone will fail to support load

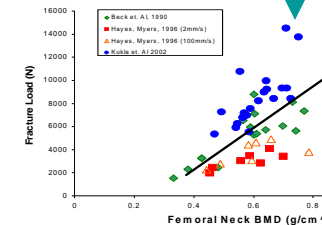


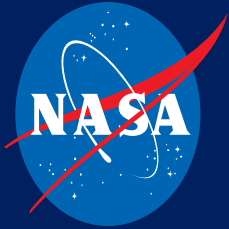
Figure 2. Summary of literature survey on fracture load as a function of femoral neck BMD

**Clinical and Engineering Characteristics of Bone Strength**



# Summary

- DXA –widely-applied medical test for terrestrial medicine but may be too limiting for operational and clinical decision-making for bone health of astronauts.
- If skeletal integrity is assessed solely by a surrogate measure of bone strength (DXA –BMD) vs. an estimate of bone strength (e.g., FE modeling), then there may be a risk of underestimating fracture probability and poorly estimating countermeasure efficacy.
- Bone Research in progress to test QCT as a risk surveillance technology and to derive new cut-points to supplement bone health standards.



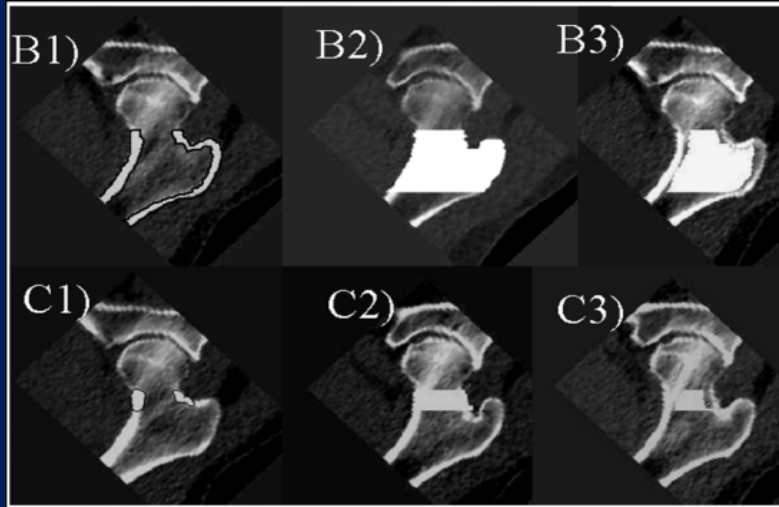
Thank you.

**QUESTIONS? COMMENTS?**

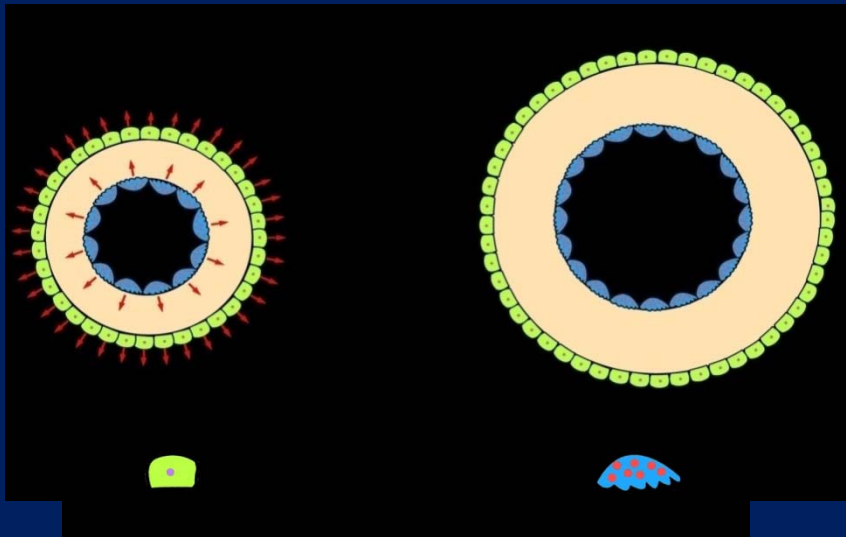
# Backup Slides



# Study on Risk Surveillance: Hip QCT



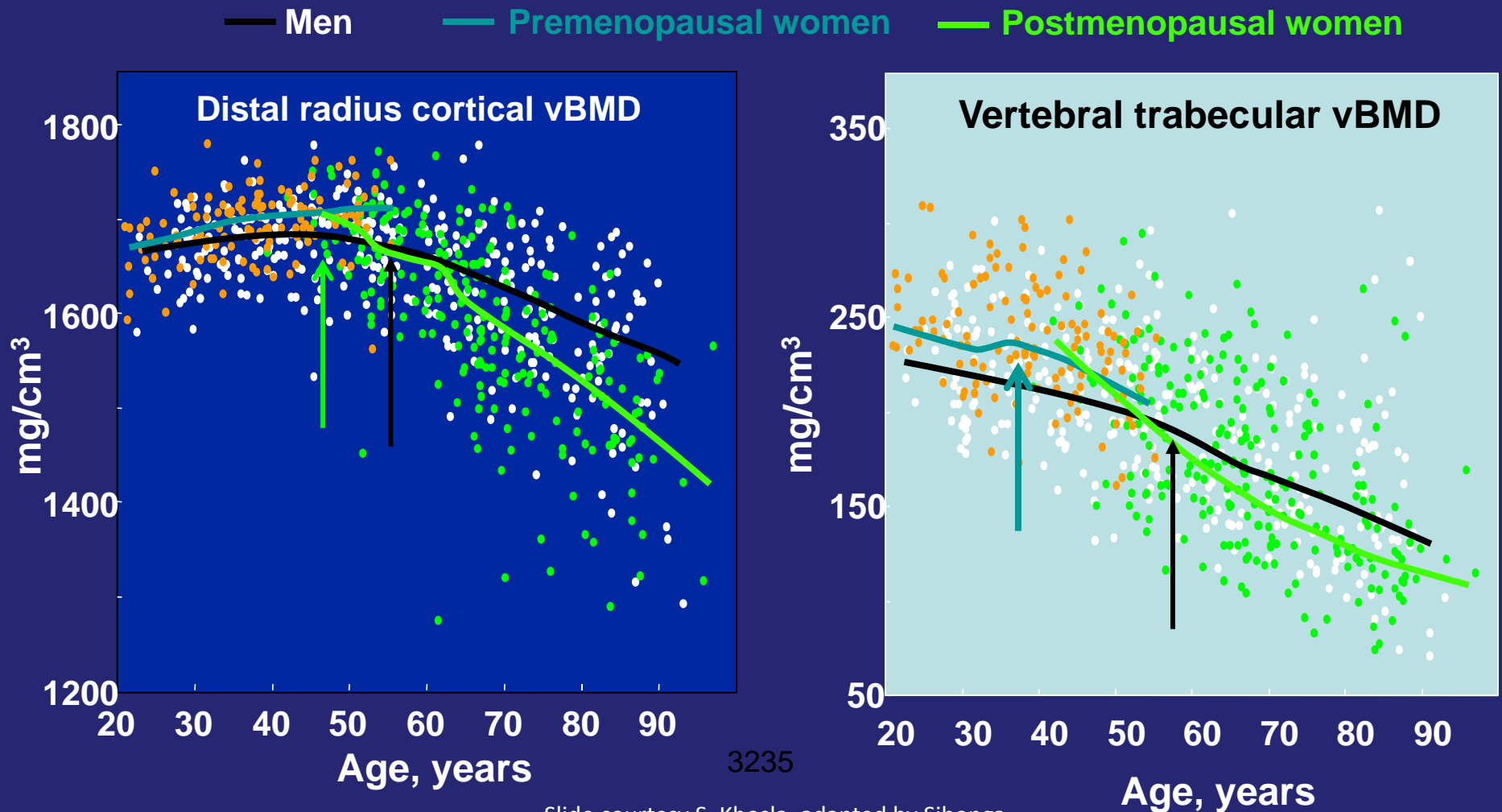
- Test feasibility of QCT protocol for surveillance of clinical trigger.
- Accumulate surveillance data for development of clinical practice guidelines (QCT and FEM)
- **Research:** Demonstrate how QCT can delineate biochemical from mechanical countermeasures. “Proof of Concept” Pilot Study



Figures courtesy of T. Lang (UCSF) and D. Carter (Stanford U)

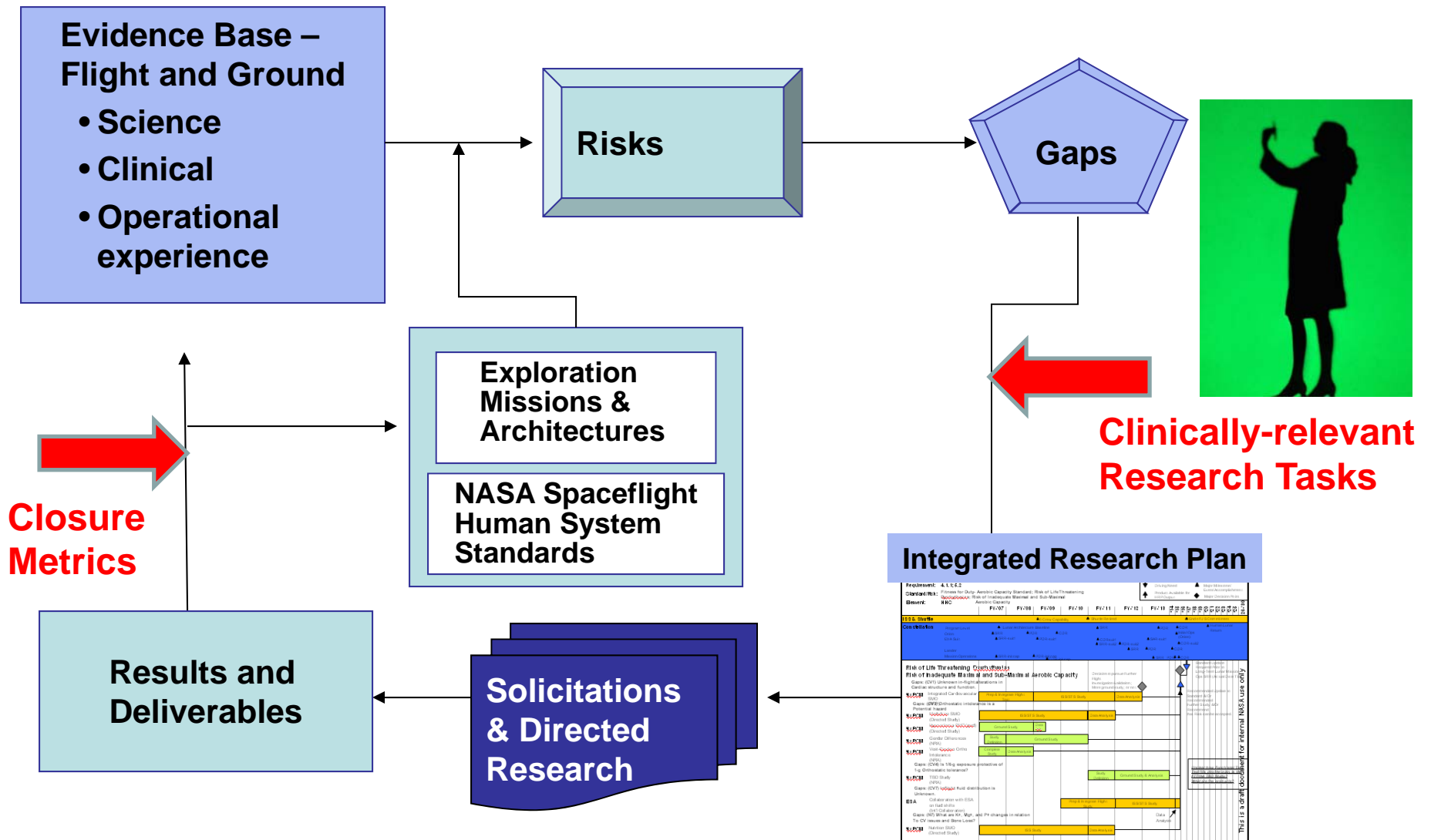
# AGE-REGRESSIONS: Trabecular bone loss occurs at earlier age than expected.

Riggs et al. JBMR19:1945, 2004.



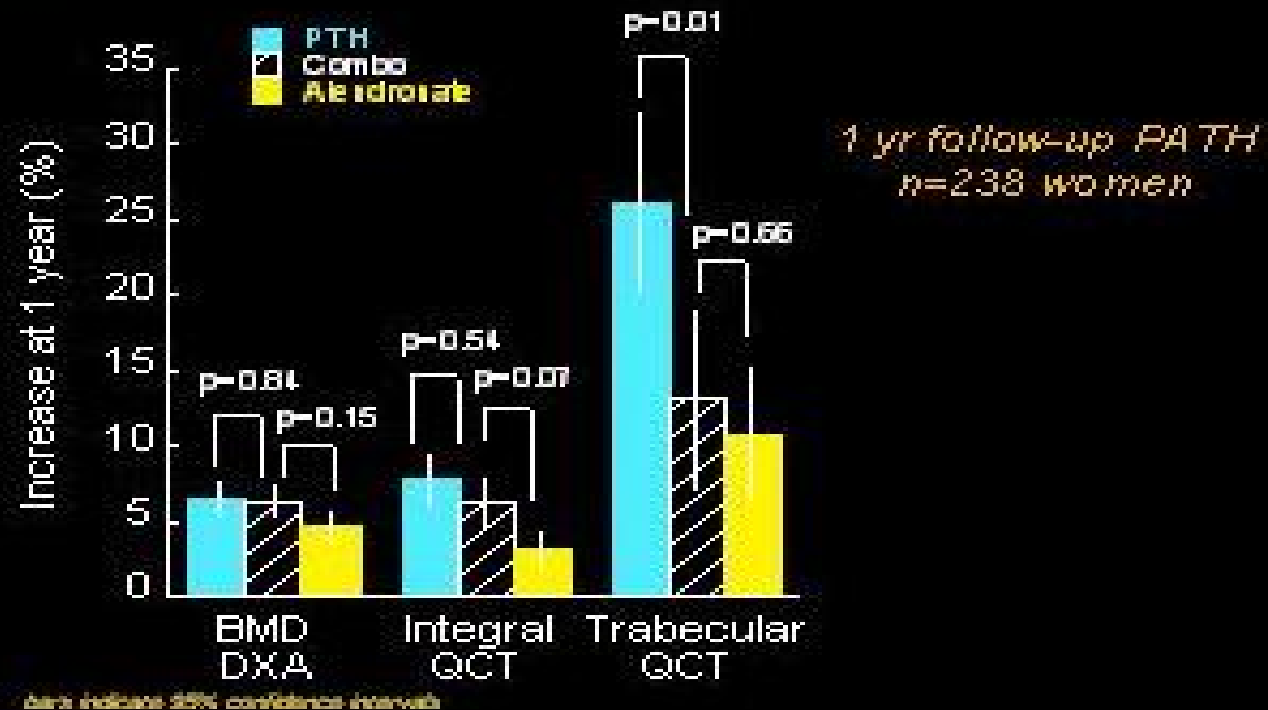
Slide courtesy S. Khosla, adapted by Sibonga

# Use of Osteoporosis Policy-makers help to translate research data to CPGs in absence of fracture data.

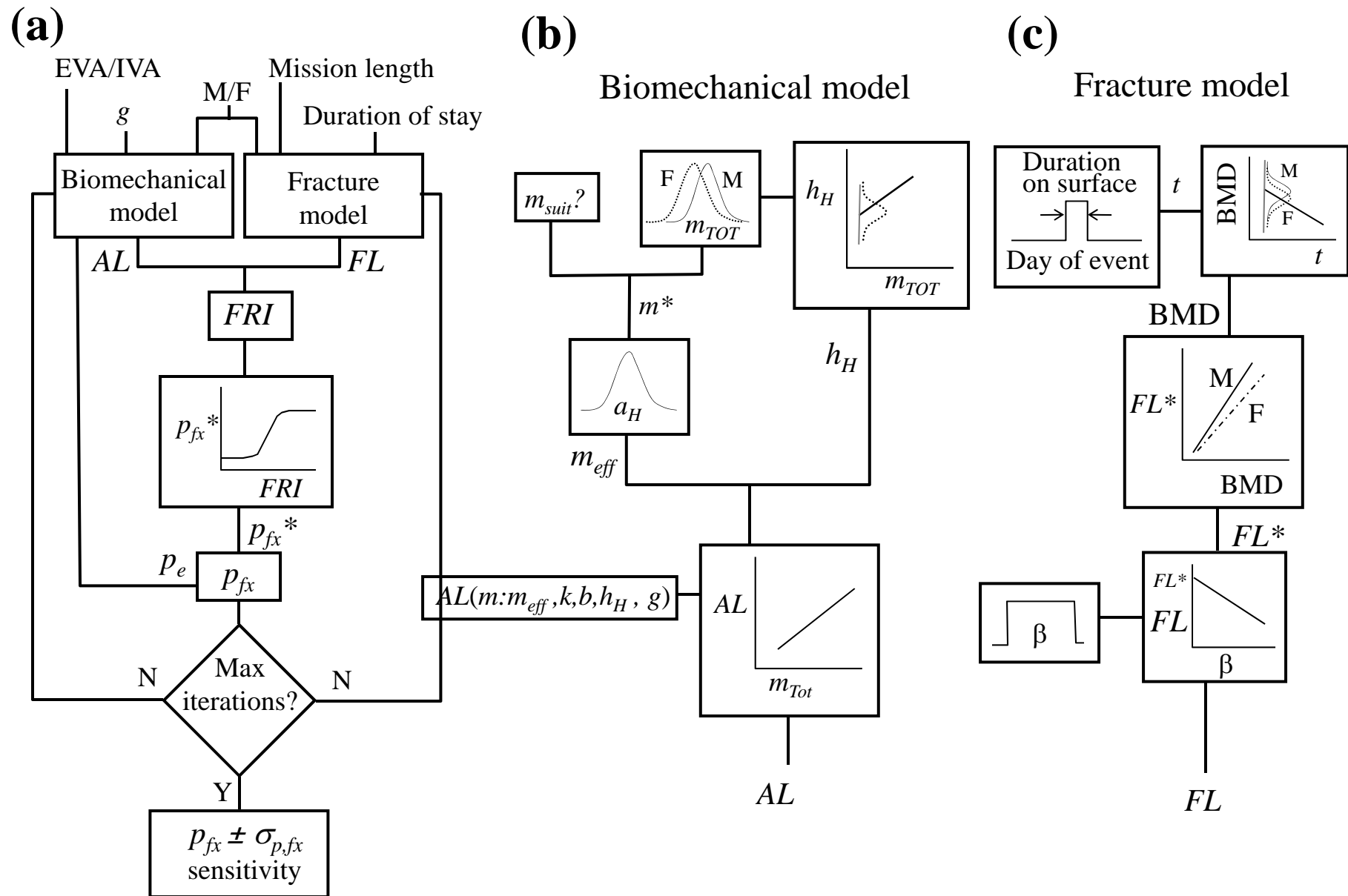


# Effects on Different Compartments of Bone (cortical vs. trabecular BMDs)

## Monitoring Drug Therapy



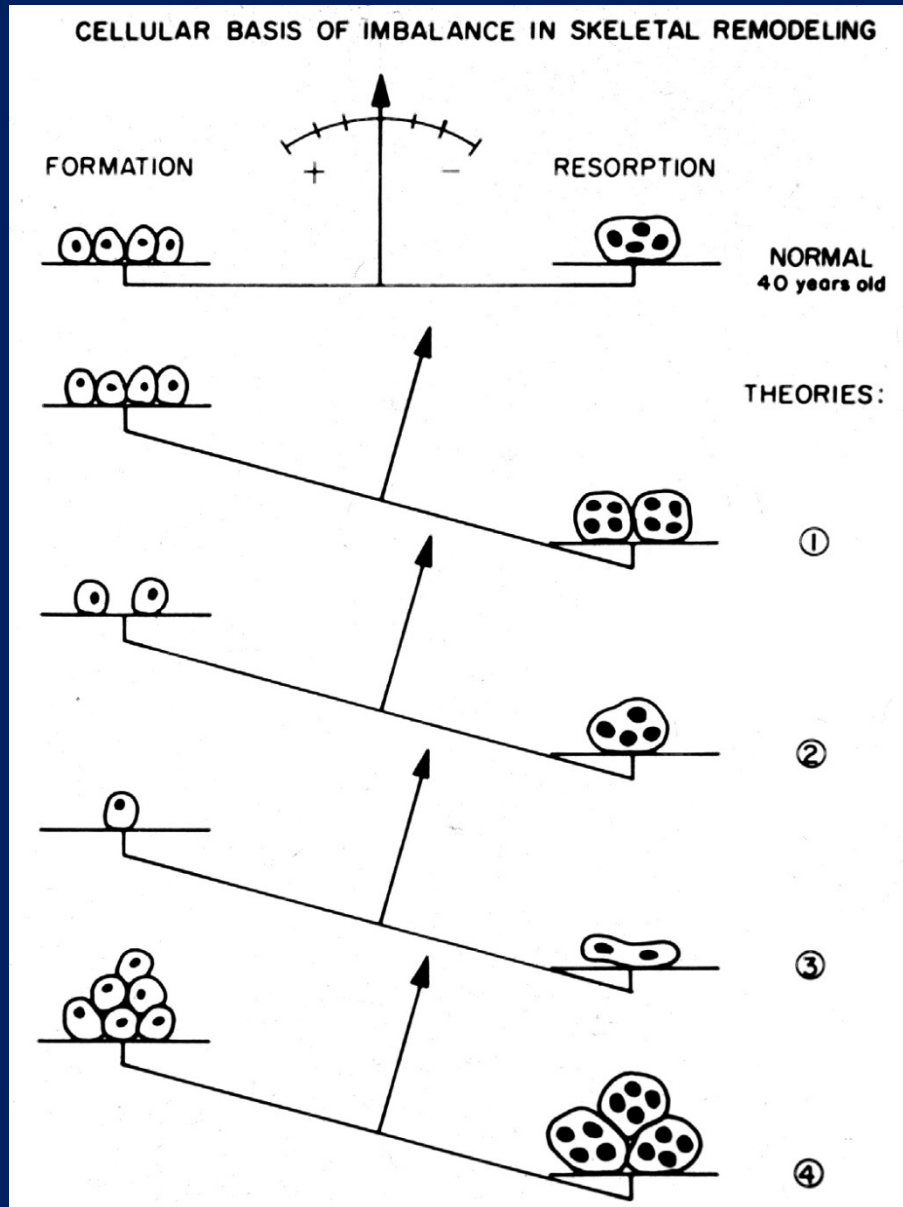
Black et al. NEJM 2003



ES Nelson et al. **Development and validation of a predictive bone fracture risk model for astronauts** NASA Glenn Research Center, Cleveland, OH

*Ann Biomed Eng*, 37(11), 2009, pg. 2337 - 2359.

## Different ways to unbalance remodeling at bone surface.



Different levels of cell number and cell activities ending in deficit of bone at the BRU.

Space?

QCT provides useful information re: causation of hip fracture, evaluation of hip fracture risk and possible targets for intervention.

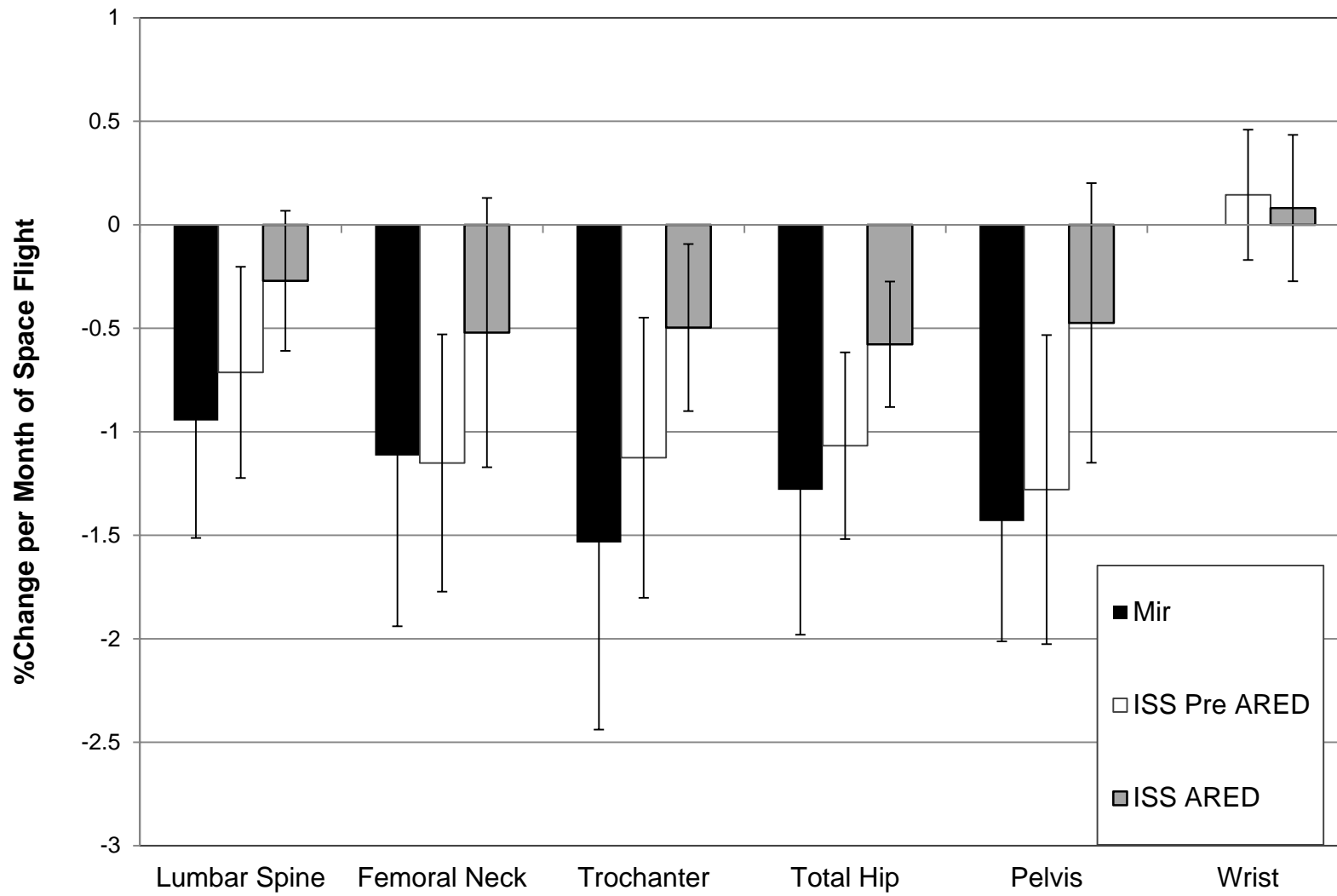
TABLE 4. HRs OF MULTIVARIATE MODELS OF SKELETAL PARAMETERS AT THE FEMORAL NECK FOR HIP FRACTURE ADJUSTED FOR CLINIC SITE, AGE, AND BODY MASS INDEX

	<i>Model A (HR per SD decrease)</i>			<i>Model B (HR per SD decrease)</i>			<i>Model C (HR per SD decrease)</i>		
	<i>HR</i>	<i>95% CI</i>	<i>p</i>	<i>HR</i>	<i>95% CI</i>	<i>p</i>	<i>HR</i>	<i>95% CI</i>	<i>p</i>
Trabecular bone, volumetric BMD (g/cm <sup>3</sup> )	—			1.65	1.15, 2.37	0.007	1.29	0.84, 1.98	0.250
Percent cortical volume	—			3.19	2.23, 4.57	<0.001	2.42	1.56, 3.76	<0.001
Minimum cross-sectional area (cm <sup>2</sup> )	—			1.59	1.24, 2.05	<0.001	1.48	1.14, 1.94	0.004
Areal BMD from DXA (g/cm <sup>2</sup> )	4.13	2.67, 6.38	<0.001	—			1.91	1.06, 3.46	0.033

Area under the ROC curve for Models A, B, and C were 0.853, 0.855, and 0.860, respectively.

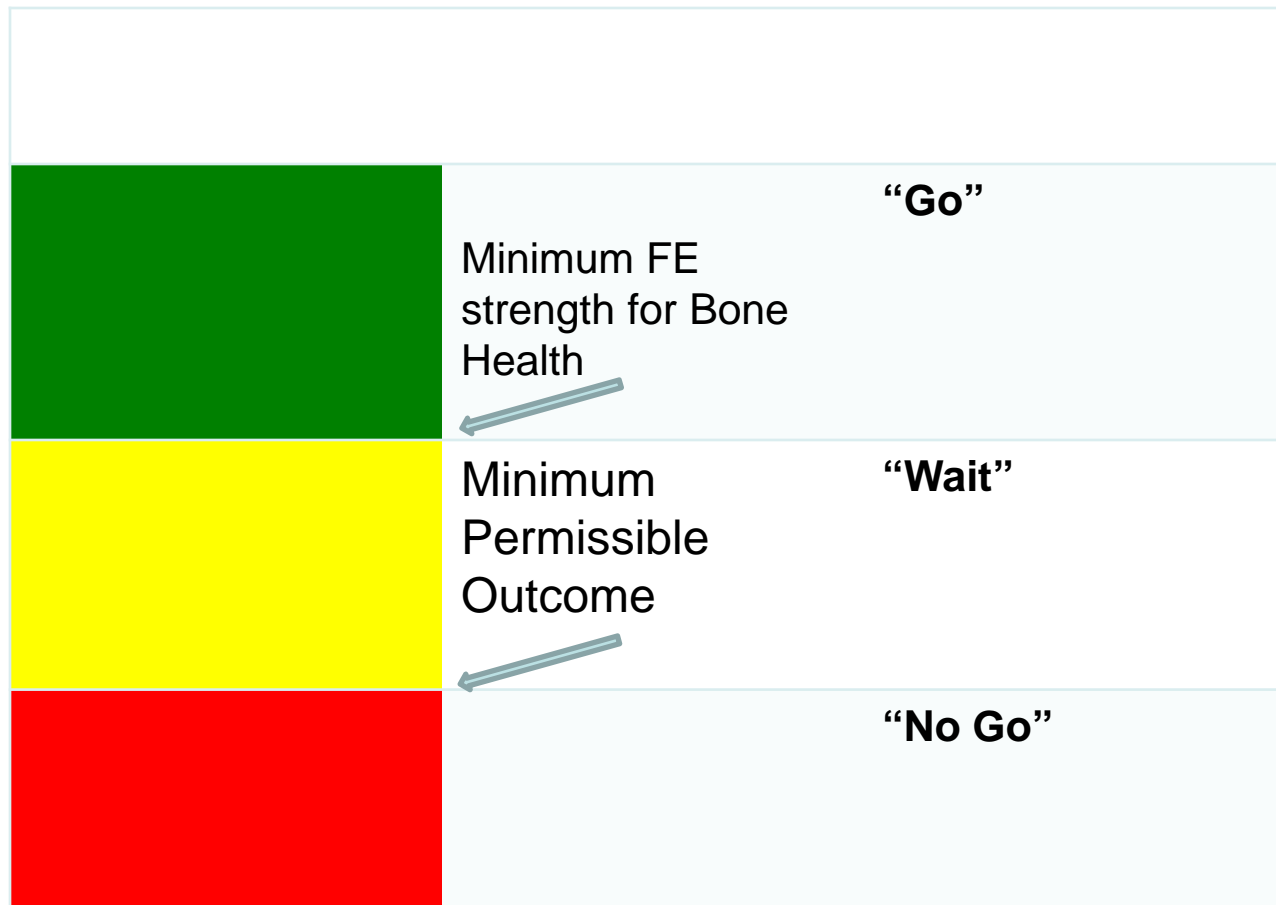
# ARED exercise **appears** to mitigate decline in areal BMD.

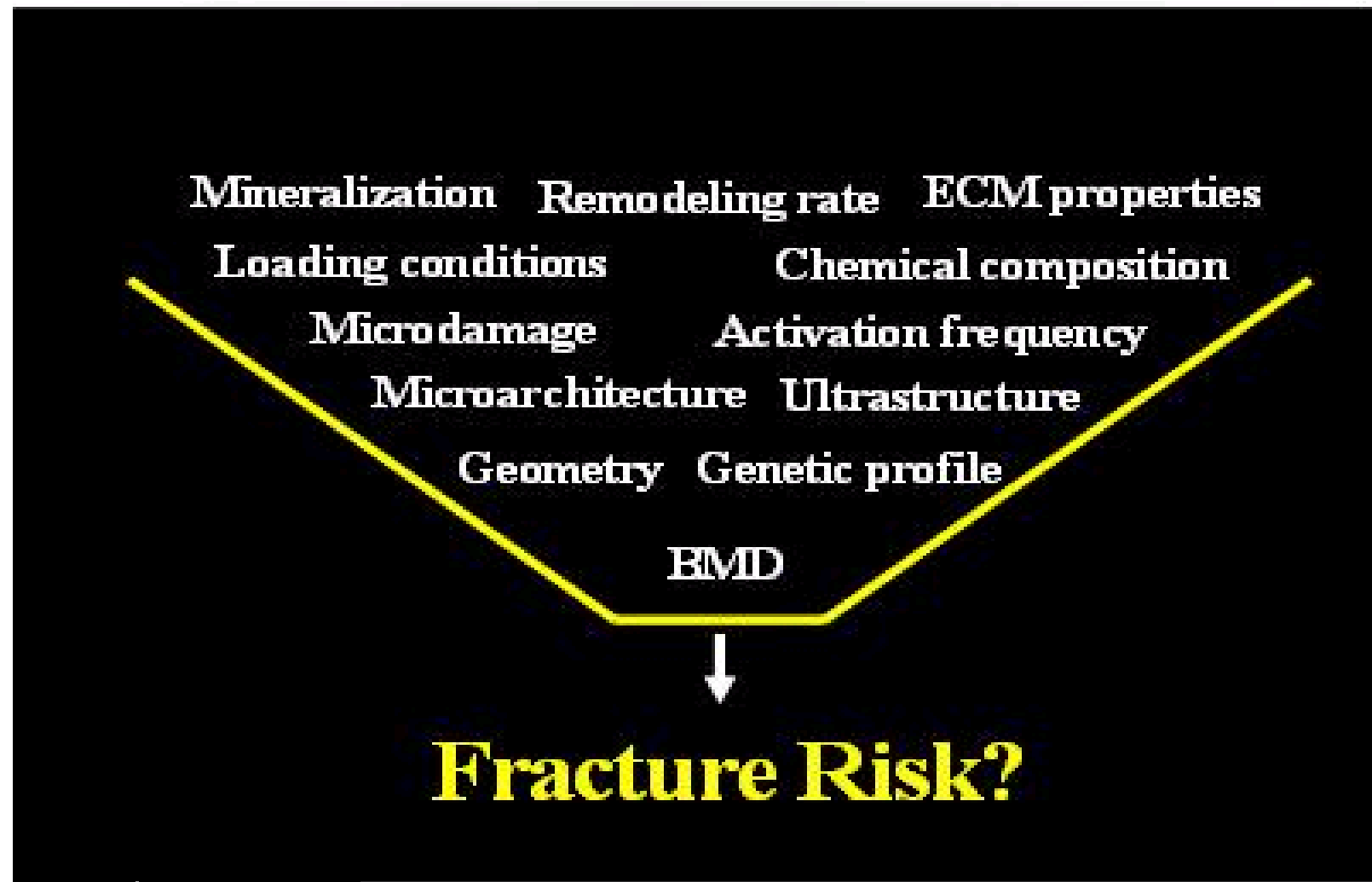
(J Bone Mineral Research. Smith et al 2012) \* *this is not ref for figure.*





# **FE Standards Combine Aging and Spaceflight Changes to Hip Strength and used together with DXA BMD Standards.**



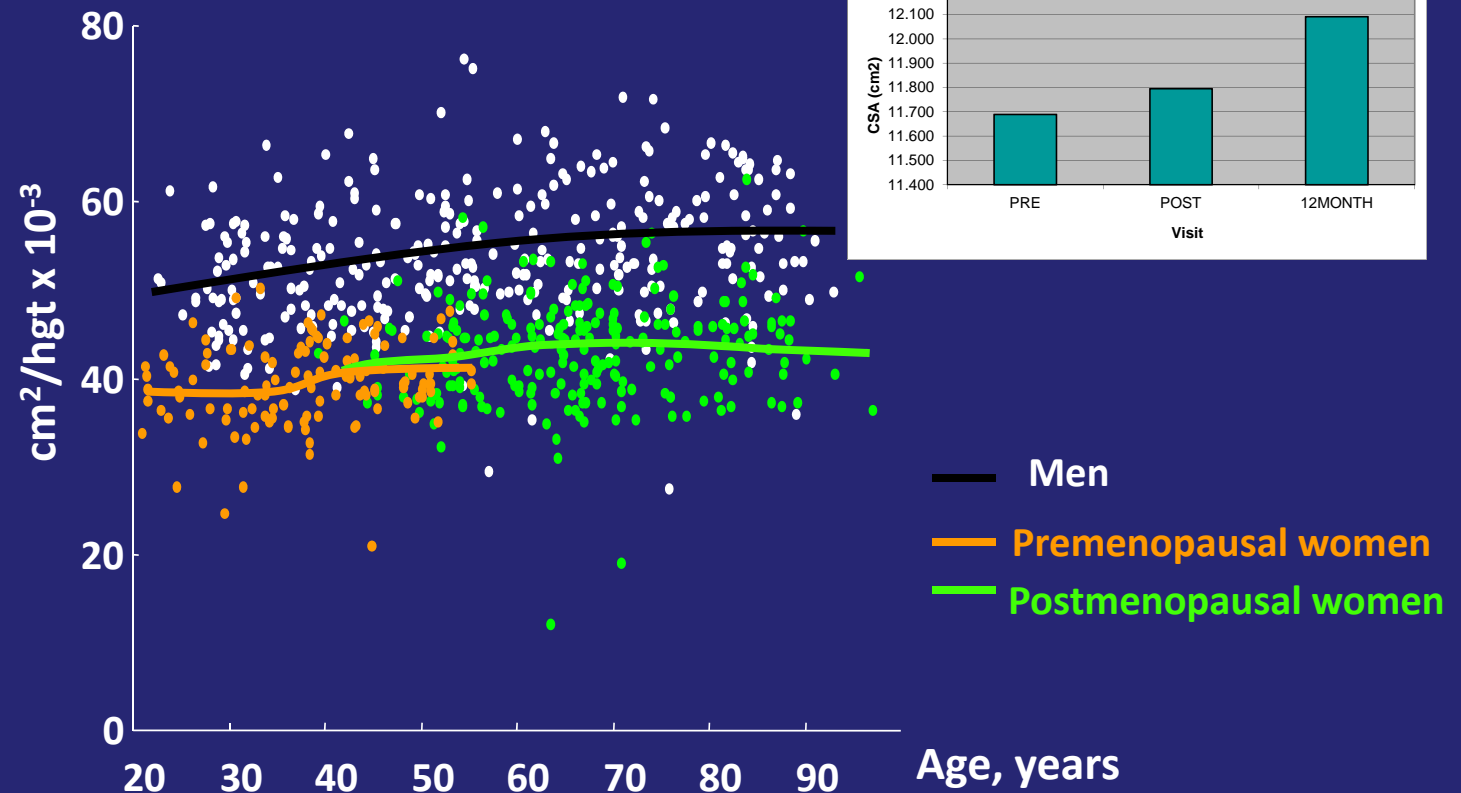


Steven Goldstein, Ph.D.

“Bone Quality: A Biomechanical Perspective”

# QCT in Population Study: Age-related Changes

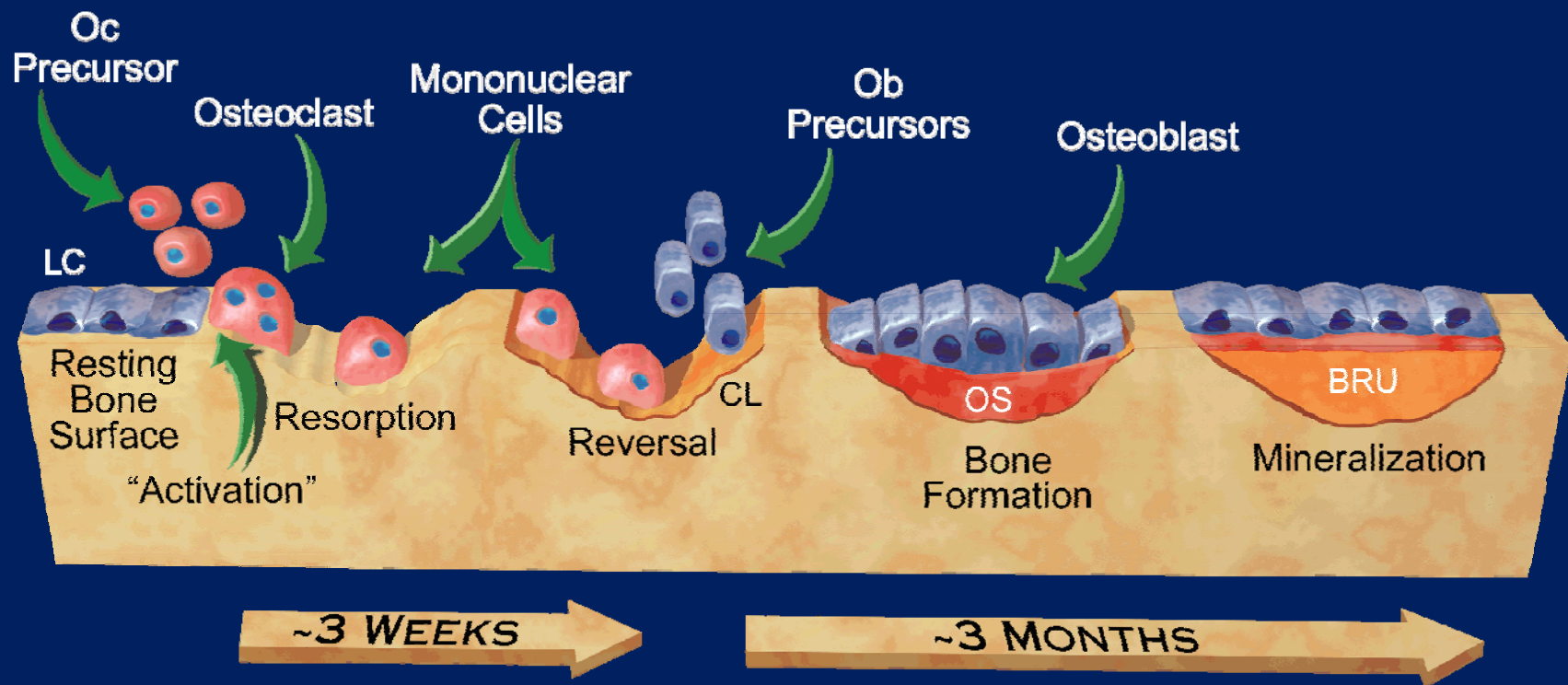
Suggests that femoral neck total area increases by outward displacement when cortex thins with age



## The long-duration astronaut – not typical subject to evaluate osteoporosis (4/2014).

- Typical space mission duration –  $159 \pm 32$ d (range 49-215d)
- Average Age –  $47 \pm 5$  y (range 36 – 56)
- Male to Female Ratio – 4.4 : 1
- Current total # per astronauts in corps – 59 of 365
- # repeat fliers – 6
- BMI – Male BMI  $25.7 \pm 2.2$  (range 21.2 to 30.7); Female BMI  $22.2 \pm 2.3$  (range 20.1 to 25.9)
- Wt and Ht- Males: Males:  $81 \pm 9$  (64 to 101);  $176 \pm 6$  (163 to 185)
- Females:  $64 \pm 7$  (54 to 81),  $169 \pm 4$  (163 to 178)
- % Body Fat: Males  $20 \pm 4$  (9 to 27); Females  $27 \pm 8$  (19 to 41)
- *MEDICAL PRIVACY A MAJOR CONSTRAINT*

# Bone Remodeling Sequence



LC = Lining Cells   CL = Cement Line   OS = Osteoid   BRU = Bone Remodeling Unit